Snow

HYDRO-CH2018 SYNTHESIS REPORT CHAPTERS: “FUTURE CHANGES IN HYDROLOGY“

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Impressum

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Summary

An important feature of snow cover is the fact that its volume and duration is subject to large year-to-year fluctuations. As frozen precipitation, snow cover is a natural water reservoir that delays precipitation to runoff and is thus of outstanding importance for the seasonal water balance in Switzerland. Over a whole year, approximately 40% (22 km3) of the annual runoff currently comes from snow melting and only 1-2 % from glacier melting. Typically, the snow cover in the Alpine region builds up over the autumn and winter months, reaches its maximum between February and May, depending on the altitude, and dominates the runoff processes during melting in the following spring and summer months.

Due to the great dependence on minus temperatures and precipitation, the snow cover reacts sensitively to temperatures above 0° Celsius and more or less precipitation. Due to climate change and the associated warming, the proportion of precipitation that falls as snow decreases measurably. In addition to this reduction in snowfall, the warmer temperatures also cause the snow cover to melt more quickly. The decline in snowfall has so far mainly affected lower altitudes, where winter temperatures often reach positive levels. The proportion of days with snowfall below 500 m above sea level has fallen by approx. 40% since 1961 and the water temporarily stored in the snow (snow water equivalent) in spring below 1000 m asl. even by approx. 75%.

As climate change progresses, this trend is likely to continue and above all affect higher zones. Even at higher altitudes, the snow cover will then start later, melt away earlier and the area of permanent snow cover will strongly diminish. Due to the projected increase in winter precipitation by the end of the century, the snow cover above 2500 m above sea level will decrease only slightly until the start of the snow melt period. All in all, however, the water stored in the snow will clearly decrease. This development will also have an effect on the water bodies. Today nival regimes, i.e. regimes shaped by snow, are shifting towards pluvial regimes, i.e. regimes dominated by rain. Overall, winter runoff increases, summer runoff decreases. By the end of the century, the proportion of runoff from snowmelt will decrease throughout Switzerland, albeit to a lesser extent than the proportion from glacier melt.

Zusammenfassung

Ein wichtiges Merkmal der Schneebedeckung ist die Tatsache, dass deren Volumen und Dauer grossen Jahr-zu-Jahr Schwankungen unterliegt. Als gefrorener Niederschlag ist die Schneedecke ein natürlicher Wasserspeicher, der den Niederschlag verzögert zum Abfluss bringt und damit eine herausragende Bedeutung für den saisonalen Wasserhaushalt in der Schweiz hat. Über ein ganzes Jahr betrachtet, stammen aktuell ungefähr 40% (ca. 22 km^3) des jährlichen Abflusses aus der Schneeschmelze und nur gerade 1-2 % aus der Gletscherschmelze. Typicherweise baut sich die Schneedecke im Alpenraum über die Herbst- und Wintermonate hinweg auf, erreicht ihr Maximum je nach Höhenlage zw. Februar und Mai und dominiert während des Abschmelzens in den folgenden Frühlings- und Sommermonaten die Abflussprozesse.

Aufgrund der grossen Abhängigkeit von Minus-Temperaturen und Niederschlag reagiert die Schneedecke empfindlich auf Temperaturen oberhalb 0° Celsius und mehr oder weniger Niederschlag. Auf Grund des Klimawandels und der damit verbundenen Erwärmung nimmt der Anteil des Niederschlages, welcher als Schnee fällt, messbar ab. Neben diesem Rückgang der Schneefälle schmilzt die Schneedecke auf Grund der wärmeren Temperaturen zudem schneller weg. Betroffen vom Schneerückgang waren bisher vor allem tiefere Lagen, weil dort die Wintertemperaturen häufig positive Temperaturen erreichen. So ist der Anteil der Tage mit Schneefall unter 500 m ü.M. seit 1961 um ca. 40 % zurückgegangen und das im Frühling im Schnee zwischengespeicherte Wasser (Schneewasseräquivalent) unterhalb von 1000 m ü.M. gar um ca. 75%.

Mit fortschreitendem Klimawandel dürfte sich dieser Trend weiter fortsetzen und vor allem auch höhere Zonen betreffen. Auch in den hohen Lagen setzt dann die Schneedecke später ein, schmilzt früher weg und die Fläche mit permanenter Schneedecke wird stark zurückgehen. Aufgrund der bis Ende Jahrhundert projizierten Zunahme der Winterniederschläge nimmt die Schneedecke oberhalb 2500 m bis zum Einsetzen der Schneeschmelze nur leicht ab. Insgesamt wird das im Schnee gespeicherte Wasser aber klar zurückgehen. Diese Entwicklung wirkt sich natürlich auf die Gewässer aus. Heute nival, also vom Schnee geprägte Regime verschieben sich hin zu pluvialen, d.h. vom Regen dominierten Regimetypen. Die Winterabflüsse nehmen insgesamt zu, die Sommerabflüsse ab. Bis Ende Jahrhundert nimmt der Anteil Abfluss aus der Schneeschmelze schweizweit ab, wenn auch klar weniger stark als der Anteil aus der Gletscherschmelze.

Résumé

Une caractéristique importante de la couverture neigeuse est que son volume et sa durée sont soumis à d'importantes fluctuations d'une année à l'autre. En accumulant les précipitations solides, la couverture neigeuse se comporte comme un réservoir d'eau naturel qui retarde le ruissellement des précipitations et est donc d'une importance capitale pour le bilan hydrologique saisonnier en Suisse. En moyenne, environ 40 % (22 km^3) du ruissellement annuel provient actuellement de la fonte des neiges et seulement 1-2 % de la fonte des glaciers. Dans l'espace alpin la couverture neigeuse s'accumule généralement au cours des mois d'automne et d'hiver, atteint son maximum entre février et mai selon l'altitude et domine les processus de ruissellement pendant la fonte au printemps et à l'été suivants.

Étant très dépendante aux températures négatives et aux précipitations, la couverture neigeuse réagit de manière sensible aux températures supérieures à 0° Celsius et à la quantité de précipitations. En raison des changements climatiques et du réchauffement connexe, la proportion des précipitations qui tombent sous forme de neige diminue de façon mesurable. En plus de cette réduction des chutes de neige, les températures plus chaudes font fondre plus rapidement la couverture neigeuse. Jusqu'à présent, sa diminution a surtout touché les basses altitudes où les températures hivernales atteignent souvent des valeurs positives. Depuis 1961, le nombre de jours avec des chutes de neige en dessous de 600 m d'altitude a diminué d'environ 40 % et l'eau stockée dans la couverture neigeuse saisonnière (équivalent en eau de la neige) au printemps en dessous de 1000 m d'altitude, d'environ 75 %.

Au fur et à mesure que le changement climatique s'intensifie, cette tendance est susceptible de se poursuivre et surtout d'affecter des zones plus élevées. Même à ces altitudes, la couverture neigeuse commencera plus tard, fondra plus tôt et la zone de couverture de neige permanente diminuera fortement. En raison de l'augmentation prévue des précipitations hivernales jusqu'à la fin du siècle, la couverture neigeuse au-dessus de 2500 m d'altitude ne diminuera que légèrement jusqu'à la période de fonte. Dans l'ensemble, cependant, l'équivalent en eau de la neige va clairement diminuer. Ce développement aura naturellement un effet sur les plans d'eau et rivières. Aujourd'hui, les régimes hydrologiques nivaux, c'est-à-dire les régimes hydrologiques dominés par la neige, se transforment en régimes pluviaux, c'est-à-dire des régimes dominés par la pluie. Le ruissellement hivernal augmente globalement, le ruissellement estival diminue. Jusqu'à la fin du siècle, la contribution hydrologique de l'équivalent en eau de la neige diminuera en Suisse, mais dans une moindre mesure que celle des eaux de fonte glaciaire.

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List of abbreviations

ACQWA (project): Assessing Climate Impacts on the Quantity and quality of Water.
asl: above sea level.
CCHydro (project): Climate Change and Hydrology in Switzerland.
CLISP (project): Climate Change Adaptation by Spatial Planning in the Alpine Space.
CHR (institution): International Commission for the Hydrology of the Rhine basin.
CHy (institution): Swiss Hydrological Commission.
CH2011 (project): Climate change scenarios downscaled to the Swiss domain in 2011.
CH2014-impacts (project): Impacts of climate change in Switzerland on different sectors.
CH2018 (project): Climate change scenarios downscaled to the Swiss domain in 2018.
CORDEX (project): Coordinated Regional Climate Downscaling Experiment.
CO2: Carbon Dioxide.
DEM (technical term): Digital Elevation Model.
ESA (institution): European Space Agency.
FOEN (institution): Federal Office for the Environment.
FUGE (project): Future glacier evolution and consequences for the hydrology.
GCM (technical term): Global Climate Model.
GERM (model): Glacier Evolution Runoff Model.
GLAMOS: Glacier Monitoring in Switzerland.
GPS (technical term): Global Positioning System.
IGOS (project): Integrated Global Observing Strategy.
LIDAR (method): Light Detection And Ranging.
MODIS (satellite): Moderate Resolution Imaging Spectroradiometer.
NAO (technical term): North Atlantic Oscillation.
NCCR Climate (institution): National Centre of Competence in Research "Climate Variability, Predictability and Climate Risks".
NCCS (institution): National Centre for Climate Services.
OCCR (institution): Oeschger Centre for Climate Change Research.
PREVAH (model): PREecipitation-Runoff-EVApotranspiration HRU Model.
RCP (technical term): Representative Concentration Pathways.
SCCER-SoE (institution): Swiss Competence Centre for Energy Research, Supply of Electricity.
SGHL (institution): Schweizerische Gesellschaft für Hydrologie und Limnologie.
SMP (instrument): SnowMicroPen.
SNSF (institution): Swiss National Science Foundation.
SRES (technical term): Special Report on Emissions Scenarios (e.g. A1B or A2 scenario).
SWE: Snow Water Equivalent.
UAV (technical term): Unmanned Aerial Vehicle

1. Introduction

1.1 Snow cover and climate change

Terrestrial snow has the largest geographic extent of all cryospheric components. It covers nearly 50 million km^2 of the northern hemisphere in winter. Snow provides a natural reservoir of fresh water by storing precipitation and delaying runoff. Snowmelt fills rivers and aquifers with water for drinking, food and energy production, and transportation. On the other hand, snowmelt floods and avalanches claim lives and property every year. The influence of snow extends from engineering, accessibility for humans and wildlife to recreation and many other aspects of daily living with significant economic implications (Hock et al. 2019, IGOS 2007,).

The timing, volume or extent of snow on the ground is always the result of an interplay between temperature and precipitation. E.g. snowfall can only be observed when precipitation is occurring during cold enough temperatures. A hereby built up snow cover can only last as long as temperatures are suitable to prevent melt. This implies that a deep snow pack depends on high precipitation amounts and sufficiently low temperatures. A snowpack therefore always represents the cumulative effects of snow accumulation and ablation during the preceding months. Seasonal snow acts as a control on summer soil-water storage and variations in snowpack are a key component in the global heat budget. Fresh snow has a high albedo and reductions in snow cover due to warming and increasing amount of black carbon in the snow are expected to contribute to polar amplification of climate change (Phitan et al. 2014).

This high sensitivity of snow to changes in temperature and precipitation makes it a primary indicator of climate change and the corresponding impacts on the redistribution and acceleration of the water cycle. Several studies demonstrate that the climate change induced temperature increase already reduces snow accumulation as a greater fraction of the precipitation falls as rain (Serquet et al. 2011), while warmer spring and summer temperatures intensify the spring snow melt in the Alps and thus cause a shift to earlier snow disappearance dates (Marty and Meister 2012).

In the Alps the snow depth and snow duration show negative trends over the past decades. The changes are typically elevation dependent, with more (less) pronounced changes at low (high) elevations (Marty 2008; Durand et al. 2009; Terzago et al. 2013; Schöner et al. 2019). Other studies found decreases in spring snow water equivalent (SWE) (Figure 2-1)(Bocchiola and Diolaiuti 2010; Marty et al. 2017a). The observed changes in snow depth and snow duration are mainly caused by a shift from solid to liquid precipitation (Figure 2-2) and by more frequent and more intense melt (Klein et al. 2016), both resulting from higher air temperatures during winter and spring. These changes in snow cover duration and snow depth will have severe consequences for winter tourism (Uhlmann et al. 2008; Steiger and Abegg 2013), water management (Gaudard et al. 2014; Addor et al. 2014) and ecology (Wipf et al. 2009; Imperio et al. 2013).

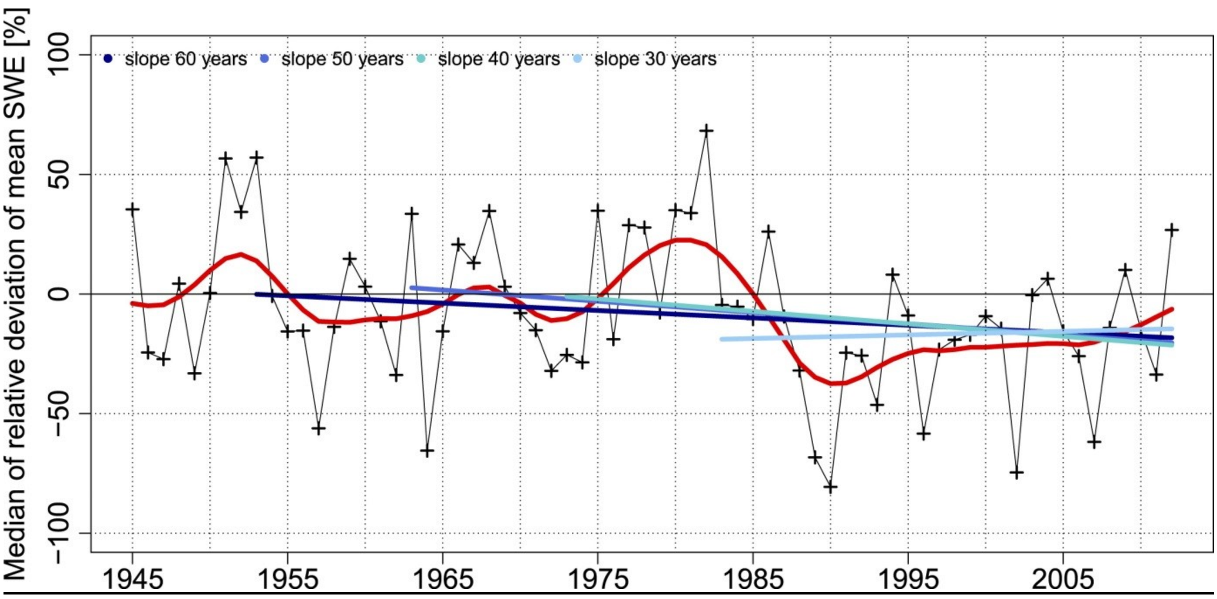

Figure 2-1: The 1 Feb relative SWE deviation compared to the long-term mean (1961–90). Annual values represent the median of the deviations of 54 in-situ Alpine stations between 1300 and 2000 m. The smoothed red curve results from a 10-yr Gaussian low-pass filter. (adapted from Marty et al. 2017a)

1.2 The role of snow for hydrology in Switzerland

The most important seasonal runoff signal in the Alps is the melt of snow (Beniston, 2012). This is because the precipitation distribution is fairly even throughout the year, and because the amount of water retained in and released from reservoirs and lakes is only a small fraction of the total (Schaefli et al. 2007). Temperature-induced changes in streamflow (rain-to-snow fraction, seasonal shift of snowmelt, glacier runoff contribution) are generally better understood than the ones caused by changing precipitation (Blaschke et al., 2011). Nevertheless, understanding long-term trends in runoff require an accurate estimate of the amount and distribution of snow accumulation during winter (Magnusson et al., 2010; Huss et al., 2014). The response of snowmelt to changes in temperature and precipitation is influenced by the complex interactions between climatic conditions, topography and wind redistribution of snow (López-Moreno et al. 2013; Lafaysse et al. 2014).

The relative share of runoff originating from snow heavily depends on the elevation of a catchment. Since more than 50 % of the country is situated above 1000 m asl, almost 25 % above 2000 m asl, it is not astonishing that a considerable amount of the annual precipitation is falling as snow in the Alps. In large parts of the Swiss plateau snowfall only contributes about 5 % to the annual precipitation sum. At 1500 m asl however this ratio is already about 30% and at 2000 m asl it increases to about 50%. The ratio is certainly varying from year to year and it also slightly differs from region to region but is heavily depending on the elevation distribution of an investigated catchment. During the winter season the snow pack accumulates in many pre-alpine and most alpine regions, whereas it melts in the spring and summer season up to altitudes of about 3,000–3,500 m asl, depending on exposure. Moreover, the existence of a snowpack and its capacity to absorb water also controls the ratio of precipitation which is lost by evaporation and sublimation. All these properties lead to a seasonal runoff dynamics which is dominated by the elevation distribution of a catchment. The role of snow as intermediate water storage for winter precipitation is of prime importance for the understanding seasonal runoff. Low elevated catchments are usually only marginally or only temporarily influenced by snow, whereas catchments dominated by nival regimes experience the peak runoff (usually in Mai and June) with values more than double the mean annual runoff. In glacial dominated catchments peak runoff occurs later (usually in July and August) and the seasonal differences are even bigger due to the additional ice melt. An example from the Brienzwiler (Aare catchment) demonstrates that the share of long-term mean annual runoff from snow (55 %) is much larger than the share from glacier ice (13%). These two numbers become equal (30 vs. 30 %) if only August is considered. However, the glacier share on runoff is clearly larger than the snow share (80 vs. 20%) in the extreme case of September 2003, following the very dry and hot summer 2003 (Stahl et al. 2017).

The seasonal differences in runoff in nival regimes are relevant in many respects: First, the annual runoff from snowmelt is important for the management of reservoirs. Second, a combination of snowmelt and heavy precipitation can lead to disastrous runoff and flooding, which can cause heavy damage in alpine areas but also in downriver lowlands. Third, a low zero degree line and therefore a larger fraction of solid precipitation (snow fall) can on the other hand dampen the impact of heavy precipitation events. Finally, a low winter snow cover preceding a dry spring plays an important role in the long-term forecast of summer drought.

1.3 Objectives of this chapter

The main objective of this chapter is to summarize and discuss the advances that have been achieved in our knowledge of the role of snow on the hydrology of Switzerland in a changing climate since the publication of the CH2014-IMPACTS report (CH2014-Impacts 2014). The revised literature includes reports commissioned by national agencies in Switzerland and neighbouring Alpine countries, as well as results from snow climatological studies published in peer-reviewed journals. An additional section is dedicated to new observational technologies that can be anticipated to play a relevant role during the next years. Finally, open research questions are outlined and recommendations about how to translate research findings into policy-relevant messages are provided.

This chapter is structured as follows:

- Review of recently published reports commissioned by national agencies.
- Review of recent advances in understanding and predicting future snow evolution, including the introduction of new technologies and techniques.
- Analysis of the implications of snow cover retreat on Swiss water resources.
- Discussion: Research gaps and open questions.
- Conclusions: Transform research findings into policy-relevant messages.

Take-home messages

Snow cover is an important water resource for the hydrology in Switzerland. Runoff from snowmelt plays a dominating role during one third of the year (March to June) in most alpine catchments.

The high sensitivity of snow to changes in temperature and precipitation makes it a primary indicator of climate change and the corresponding impacts on the water cycle. The observed temperature increase reduces snow accumulation at low elevation as a greater fraction of the precipitation falls as rain, which together with the intensification of the snow melt causes shortening of the snow duration.

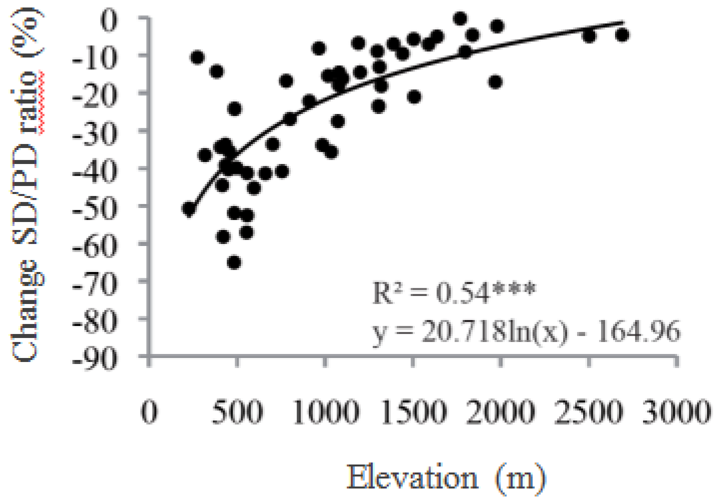

Figure 2-2: Changes in the ratio of snow fall days (SD) to precipitation days (PD) as a function of altitude (m asl) of 52 Swiss observer stations for the 47 winters (DFJ) between 1961 and 2008 (adapted from Serquet et al. 2011)

2. Review of recent reports

2.1 Snow declines and its consequences as seen in recent reports

In recent years, several reports from national agencies, universities and research centres have been published that investigate the impacts of climate change in Switzerland. In this section, five major reports (see Table 1-1 in the glacier chapter) that include analyses of climate change impacts on Swiss snow cover and their associated water resources are revised and discussed:

A. “Auswirkungen der Klimaänderung auf die Wasserkraftnutzung” (Schweizerische Gesellschaft für Hydrologie und Limnologie (SGHL) und Hydrologische Kommission (CHy) 2011)
B. “Effects of climate change on water resources and waters” (Federal Office for the Environment FOEN 2012)
C. “Assessing Climate impacts on the Quantity and quality of Water” (Beniston et al. 2013)
D. “CH2014-Impacts” (CH2014-Impacts 2014)
E. “The snow and glacier melt components of the streamflow of the River Rhine and its tributaries considering the influence of climate change” (Stahl et al. 2017).

The first four reports project future impacts of climate change, whereas the fourth one presents results of a detailed hydrological simulation of the Rhine River catchment, including an explicit quantification of the runoff-share of snowmelt.

The snow part in report A summarized several independent studies on future runoff evolution and on the consequence for hydropower generation from several high alpine catchments. According to the reported results the duration of the seasonal snow cover above 1200 m asl will shorten by 25 days per degree warming. However, the authors emphasize that the model uncertainties are quite high at elevations between 1200 and 2000 m asl. The seasonal maximum SWE in the higher part of the catchments will decrease by 50 to 70 % until the end of the century (Figure 2-3 and the variability between snow scarce and snow abundant winters will be much smaller than today. A nowadays snow scarce winter will become normal by the end of the century. The authors conclude that the high alpine area which is affected by rain events will be much larger than today, especially in winter. Consequently, the runoff will increase in winter und decrease in summer. Annual runoff from glaciated catchments may decrease towards the end of the century due to the decreasing glacier melt. Nevertheless, annual power production may increase due to the temporally more balanced runoff. .

Regarding snow, report B merged the result of a new study by Zappa et al. (2012) with the summary of report A. The new study reveals that nowadays (1980-2009) about 40% of the total runoff out of Switzerland originates from snow melt. This is about 22 km³ water per year. Model simulations estimate that this number will drop by 40 % towards the of the century (Figure 2-4), which would imply an annual share of only 25 % from snow melt. The projections for the end of the century show that the snow accumulation occurs slower and the maximum will be reached about two weeks earlier than now. An increase in winter temperatures of about 3° C by 2070–2099 will raise the snowline by around 500 metres. As precipitation amounts in winter may increase over the course of the century, it is possible that greater amounts of snow will fall at very high altitudes during this season. However, the total area covered by snow in winter will 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. This will have a direct impact on runoff and its distribution over the course of the year. Finally, the authors conclude that the 22 km³ of water to runoff in Switzerland are considerably more than the amount contributed by annual glacier mass loss (1 km³). As temperatures continue to rise, so will the snowline, and regions up to about 3500 m asl will be increasingly snow-free in summer. By the end of the century, snow cover at altitudes below 3500 m asl 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.

Report C summarizes the results from the ACQWA-project (ACQUA 2013), which was a large inter-disciplinary project in which the vulnerability of water resources to declining snow and ice due to global warming was assessed. Although the project produced results for several mountain regions in the world, here only the main results obtained for the Swiss Alps are outlined. One of the main conclusions is that elevation-dependent impacts of warming can be expected in the Rhone basin, with the largest impacts at high-elevation sites. Alpine snow cover will decline due to temperature increases (more rain/less snow), particularly at mid-latitude locations between 1000-2000 m asl. Earlier snow-melt by 5-10 days and an increased melt in April and May is projected for these elevations. Major changes in the total runoff of the Rhone basin are likely to be small, but local changes or temporal changes at high-elevation catchments can be very large. Climate change impacts in snow dominated catchments show that water managers and users will need to adapt to changes in the quantity and timing of water resources. This is not only relevant at local and regional scale, but also to communities and economic sectors downstream who are reliant on a range of goods from mountain regions and their resources (e.g. electricity, water, water storage in the form of ice and snow).

Report D on the impacts of climate change in Switzerland included a chapter “Cryospheric aspects of climate”. In that chapter, a distributed physical snow cover model was forced by the CH2011 climate scenarios (CH2011, 2011) to quantify how the snow cover will be affected by climate change in upper Rhine and Aare catchment. It could be demonstrated that the projected snow cover changes are relatively small in the near term (until 2035), in particular at higher elevations above 2000 m asl. For instance, the spread in the projected snow cover for this period caused by different climate model chains is larger than the difference between the reference period and the model chain exhibiting the most moderate change. Towards the end of the century, however, much larger changes with the potential to fundamentally transform the snow dominated alpine area became apparent. These changes include a shortening of the snow season by 5–9 weeks for the A1B scenario (Schmucki et al. 2015). This is roughly equivalent to an elevation shift of 400–800 m. The slight increase of winter precipitation and therefore snow fall projected in the CH2011 scenarios (with high associated uncertainty) can no longer compensate for the effect of increasing winter temperatures even at high elevations. In terms of SWE, the projected reduction is up to two thirds toward the end of the century. A continuous snow cover will be restricted to a shorter time period and/or to regions at increasingly high elevation. This implies that a multi-day snow cover is projected to become a rare phenomenon in the Swiss Plateau assuming that the future climate is evolving according to a non-intervention scenario like A1B or A2. The authors state that a declining snow reservoir in the Alps will prolong periods of low river flow in summer in many parts of Europe toward the end of this century (Farinotti et al., 2012). A significant reduction of winter snow cover will also reduce soil moisture during dry springs and thus exacerbate the impact of hot summers. Together with the decreasing glacier melt, this can have severe consequences for several economic sectors including agriculture, hydropower generation, water supply and river navigation. Furthermore, increasing river and lake temperatures may present a problem for parts of the aquatic ecosystem (Wedekind and Küng, 2010). In the same report the chapter "Hydrological responses to climate change" reached the following conclusions: Climate change, and especially the higher temperatures associated with it, will cause a shift in the runoff regime from nival to pluvial in catchments that are not strongly influenced by glacial meltwater. Accordingly, an increase in the variability of runoff throughout the year and from year to year, resulting in lower stability and lower predictability, is another challenge that will need to be met in the future. A more flexible and adaptive water management will be needed to deal with a more irregular and longer flood season (Köplin et al. 2014) and an expected increase in the frequency of occurrence of extreme events such as droughts and floods.

Report E contains the most recent hydrological study targeting at the runoff contribution of snow and glacier melt to the river Rhine (Stahl et al. 2017). The authors conducted a detailed simulation of the past and current hydrology of the Rhine basin using models of different complexity and for the period 1901 to 2006. Model complexity was chosen depending on the characteristics of the simulated terrain along the river basin, and rain, snow- and ice-melt contributions to runoff were simulated explicitly. One important result considering past climate conditions was the large relevance of snowmelt along the Rhine River. The mean annual fraction of snowmelt in Basel was modelled as 39 %, compared to only 2% originating from glacier melt. These numbers agree well with estimates in previous modelling studies. Thanks to the daily resolution of the modelling this study could, for the first time, specifically quantify the snow and ice melt component during extreme low flow years such as 1921, 1947, 2003. While the maximum daily fraction of glacier melt during summer 2003 (i.e. end of August) was 25 %, the mean snowmelt fraction during the same time was still 20 %, demonstrating the significant role of the snow cover for runoff even after a hot and dry summer. Therefore, the authors conclude that this highly relevant contribution of snowmelt to streamflow suggests that changes in snow cover and timing of snowmelt as a contribution to runoff will play a crucial role in the future.

2.2 Open questions in the reviewed reports

By far the largest question mark in all reports is the development of future precipitation. In contrast to temperature projections, projections for precipitation still show a large spread between different climate model chains. Both increasing and decreasing precipitation is found for the Alps, and also the spread between different regions is large. Modelled changes are small for the near future (2035), but can range between +30 % and -20 % for extreme scenarios towards the end of the century. Since at least part of this precipitation will fall as snow, the future mountain snow cover will be affected accordingly. The uncertainty of the projections triggers the question whether the anticipated increase in winter precipitation will be able to compensate for the expected reduction in snowmelt runoff in spring. So far, another important limitation is the fact the most projections are based on the so-called delta change method (Bosshard et al. 2011), which assumes that future inter-annual variability is unchanged.

Take-home messages

During the period 2010-2014, a series of reports targeting at climate change impacts on water resources were commissioned by Swiss national agencies. The corresponding studies have included numerical simulations of future snow changes and their contribution to runoff.

All studies project significant elevation dependent reductions (between 50% and 97%) in the snow volume by 2100 assuming the A2 emission scenario. However, the large spread in the projected temporal and spatial precipitation evolution by the different climate models produces relatively large uncertainties.

A recent report commissioned by the International Commission for the Hydrology of the Rhine River incorporated the effect of snow cover in several hydrological models for the Rhine River basin. Runoff from snowmelt was determined to provide a significant contribution to the catchment runoff, even during hot and dry summer months as last experienced in 2003. In Basel, for example, the mean annual fraction of snowmelt was modelled as 39%, compared to only 2% originating from glacier melt.

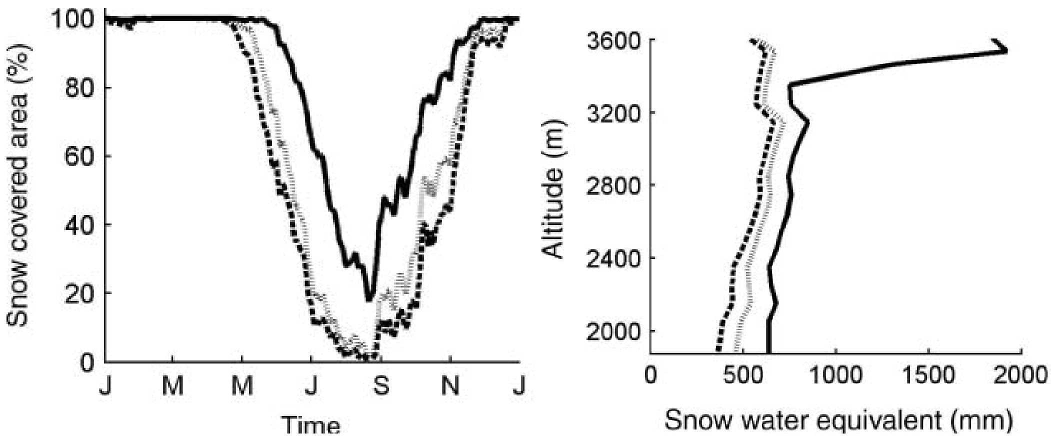

Figure 2-3: Snow covered area as function of time of the year (left) and distribution of seasonal maximum SWE as function of altitude (right) for today (solid line) and for the end of the century (2071-2100) and the IPCC A1B (grey dashed) and the A2 (black dashed) scenario in the Damma-Reuss catchment (adapted from Magnusson et al. 2010).

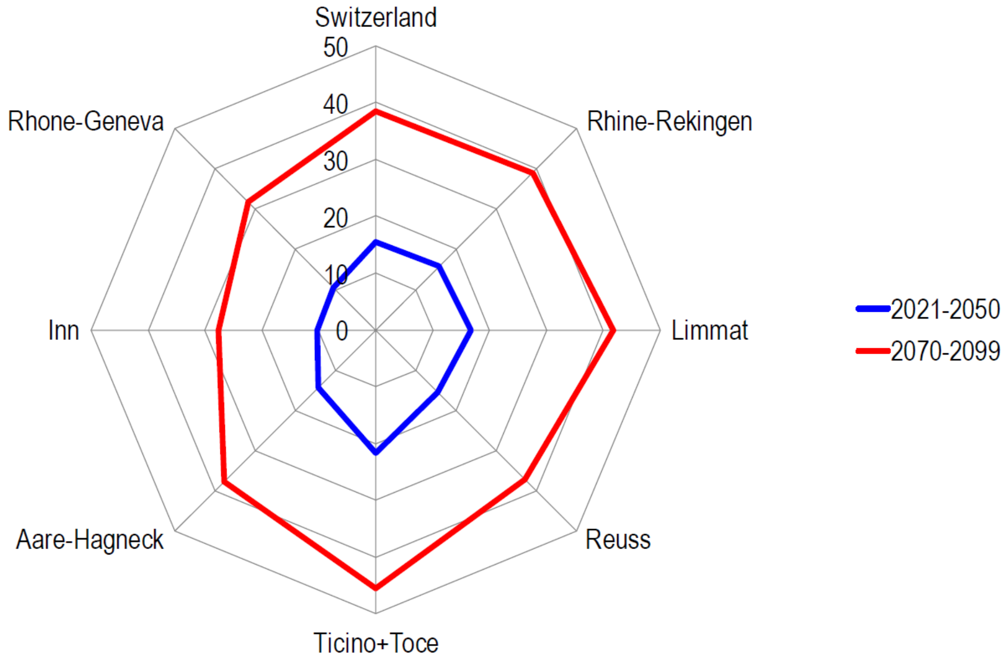

Figure 2-4: Projected decrease of meltwater from snow shown as a percentage of total runoff for all large catchments in Switzerland towards mid and end of the century for the A1B scenario (adapted from Zappa et al. 2012)

3. Progress in understanding and predicting future snow evolution

3.1 State of literature

A longer sequence of low snow winters in the Alps, as it was observed between the late 1980's and mid 1990's, led to the question if this was caused by climate change or natural variability. The only study published during this period had to limit its analysis to a few stations and to the 50 years between 1945 and 1994 (Beniston et al. 1997), and it was realized that the available snow data was insufficient to prove the uniqueness of such a sequence. A national research program on climate change and natural hazards (NRP31) in the mid 1990's allowed for digitization of archived snow data, combination of overlapping series, and quality-checking of already available data series. This work notably enabled two studies, investigating variability and trends in archived snow-cover data (Laternser and Schneebeli, 2003; Scherrer et al., 2004). Both studies found a decrease of the snow depth since the mid 1980's for low-lying stations. This decline could be linked to anomalous warm winter temperatures and more intensive spring snowmelt (Marty and Meister 2012). The step-like increase of temperatures could be associated with (a) the longest observed period with a strong, persistent, positive North Atlantic oscillation (NAO) index and (b) series of extended blocking high-pressure events (Scherrer and Appenzeller 2006; Marty et al. 2008). In terms of implications, these studies focused mainly on the impact of snow depth or snow duration changes on winter tourism and less on water resources.

Most of the snow-hydrological analyses related to climate change were carried out in the frame of three projects: CCHydro (funded by the Swiss Federal Office for the Environment), FUGE (funded by the Swiss National Foundation in the frame of the National Research Programme 61) and ACQWA (funded within the 7th framework program of the European Union). The projects were all dealing with water and climate change in general, but also analysed the role of snow as an important water resource in Switzerland. The projects were an important basis for the four reports mentioned in the former chapter. An additional project, founded by the European Union Climate Change Adaptation by Spatial Planning in the Alpine Space (CLISP) program, had a partial focus on snow resources as well. In fact, future projections for Alpine water resources based on different scenarios were performed in high spatial resolution for the Rhine and Inn catchment (Bavay et al. 2013).

As a result of this intense scientific activity, the future of the Swiss snow cover has been increasingly included in the scientific discussions about climate change. Facilitated by the availability of high-quality observations for verification, moreover, case studies in the Alps are frequently used as a reference for other regions. All these studies demonstrate a clear impact of rising temperatures on snow cover depth and duration Since the evolution of the snow cover at elevations below 1400 m is dominated by temperature (Moran et al. 2013) the projected response has much smaller uncertainties at low elevation than at high elevation. For the latter, in fact, precipitation variability has a non-negligible impact. Even if the general consequences of climate change on the Swiss snow cover are consistent within the mentioned studies, significant uncertainties and differences are still found. This is mainly because of divergent climate scenarios or different strategies for the preparation of future meteorological data as input for the snow models.

3.2 Recent advances

A recent study by Klein et al. (2016) investigated past trends of snow duration and maximum snow depth over the period 1970–2015 in the Swiss Alps, based on eleven stations between 1139 and 2540 m asl. The results show a clear reduction of the snowpack, irrespective of elevation or region, and a clear shortening of the continuous snow cover duration (-8.9 days per decade on average). The reduction in snow cover duration is mostly the result of earlier snowmelt (on average by 5.8 days per decade), rather than of later snow onset. The authors also found a general decline in the annual maximum snow depth. Moreover, the time of maximum snow depth also occurred earlier, and was highly connected to the snowmelt date and much less to the time of snow onset, illustrating the impact of the spring temperatures and of the earlier start of the melting period on the snow season.

Similar to the afore-mentioned study, past snow trends were so far always analyzed based on snow fall or snow depth. A new study by Marty et al. (2017a) analyzed for the first time long-term SWE data series and demonstrates that the Alpine snow water resources have been decreasing during the last six decades at least (Figure 2-5). This is true for all elevations, including the highest ones. A spatial analysis revealed that strength or significance of the SWE reduction is independent of the geographical position within the Alps. Low-elevation stations less frequently demonstrate significant trends than higher ones, due to the higher inter-annual variability. The observed decreases are clearly larger for April than for February. Trends in April also show a clear elevation dependency. For the last 45 years, for example, relative April SWE-loss ranges from 80% at lowest elevations (<1000m asl) to about 10% in the highest elevations (at 2500 m asl). In absolute terms, this implies a decrease of about 1 mm and 20mm per decade at the lowest and highest stations, respectively.

Regarding the future evolution of snow water resources in Switzerland, two new studies demonstrate that runoff is mostly affected by the decrease in continuous snow cover and in the mean snow depth, especially if dry weather conditions prevail. The projected relative reductions of SWE towards the end of the century for the A1B scenario are in the order of 35%, 85% and 95% at 2500 m, 1500 m and 500 m elevation, respectively (Schmucki et al. 2015), which drastically reduces the amount of snow mass available for runoff. The second study (Marty et al. 2017b) used a wide range of climate and emission scenarios to show that the duration and mass of the snow cover in typical Alpine catchments such as the Aare (Figure 2-6) and Rhine will shrink until the end of the century independently of the emission scenario and the climate model used. The authors also demonstrate that the snow loss could be reduced by about 40% if global warming was to be limited to 2 degrees. The results of these two studies are corroborated by the widespread projected trend of decreasing snowfall in ensemble of the newest generation of RCMs (Frei et al. 2018) and clearly decreasing trends of snow depth in the French Alps (Verfaillie et al. 2018)

Both of these studies applied a delta-change approach to produce meteorological time series of the future, despite the fact that this method is not capable of describing possible changes in temporal variability. A recent study by Keller at al. (2017) demonstrated that the alternative method of using a weather generator does not generally give different results as long as the summer season with the projected large change in the dry-wet structure is not included.

The question how strong maximum winter SWE impacts summer low flow was investigated by Jenicek et al. (2016). The results showed that a decrease of maximum SWE by 10 % results in a decrease of minimum discharge in July by 6–9 % in catchments higher than 2000 m asl. This effect was smaller in middle- and lower-elevation catchments with a decrease of minimum discharge by 2–5 % per 10 % decrease of maximum SWE. The authors also demonstrated a higher sensitivity of summer low flow to snow accumulation in Alpine catchments compared to lower-elevation pre-Alpine catchments.

A recent micro-meteorological study in an Alpine catchment demonstrated that turbulent sensible heat fluxes over typical melting patchy spring snow cover snow are strongly overestimated in all energy balance models (Mott et al. 2017). This influences the heat exchange between the snow cover and the overlying atmosphere and has strong implications for hydrological modelling covering an entire ablation season.

Within the CH2018 initiative, new climate scenarios for Switzerland have been produced (CH2018, 2018). These scenarios are based on the latest set of simulations for the European climate from the Coordinated Regional Climate Downscaling Experiment (CORDEX). The new set of scenarios provide the standard input variables for future climate change studies in Switzerland, including those addressing future snow changes and related impacts.

3.3 New technologies and remote sensing products

Complementary to advances in climate and snow modelling, some important advances have recently been achieved in the domain of monitoring techniques. These technologies can be expected to be important in the validation and further development of modelling approaches, ultimately helping to reduce the uncertainties of future projections.

New techniques are in development in the domain of in-situ monitoring of snow depth and SWE. A new multipoint laser snow depth sensor helps to close the gap between standard ultra-sonic sensors and the single point laser sensor (Kim et al. 2014) Low-cost GPS sensors can be used to detect snow depth and SWE simultaneously (Koch et al. 2019). Electronic handheld devices like a self-recording snow depth probe (Sturm 1999) or a high-resolution penetrometer for snow, the SnowMicroPen (Proksch et al. 2015) have been developed to efficiently investigate the small-scale heterogeneity of snow depth or snow density. A combination of a cosmic ray sensor and weather radar composites have been successfully applied to spatially integrate SWE over a Swiss glacier (Gugerli et al. 2019). High-resolution monitoring of snow surfaces by laser scanning has been successfully applied to map the snow distribution. The technique allows for detailed DEMs to be acquired with frequent time intervals and the necessary instruments can be either terrestrial (Bühler et al. 2009) or aerial (Gruenewald and Lehning, 2011). The relatively high costs of the instruments, the restricted spatial range and temporal availability have, however, limited the widespread extension of the technique. The use of close-range photogrammetry based on Unmanned Aerial Vehicles (UAVs) has lowered the cost of obtaining repeated DEMs but is still restricted in regard to the area and temporal availability (Bühler et al. 2016).

In addition to classical remote sensing products, some satellite records are becoming long enough to be used for climatological studies (Hüsler et al. 2014). Moreover, a recent generation of satellite products (ESA Sentinel) is anticipated to significantly improve the monitoring of snow area and snow mass. This will produce more accurate validation datasets for snow models operating at the larger scale, thus fostering their development (Lievens et al. 2019).

Take-home messages

Past trends in Alpine snow water resources have recently been studied on the basis of long-term snow water equivalent measurements. The results show a clear decline, especially in spring. The loss ranges from 80 % below 1000 m asl to about 10 % at 2500 m asl for April 1 since the 1960's.

The research focus has recently targeted future projections of snow water resources. The projected relative reductions of the mean SWE towards the end of the century in a typical large Alpine catchment are in the order of 70 % for the A2 scenario.

New monitoring techniques, such as UAVs or terrestrial and airborne laser scanning, but also new satellite products with increased spatial and temporal resolution will play an important role in the years to come. The acquired data can be anticipated to foster model improvements and better process understanding.

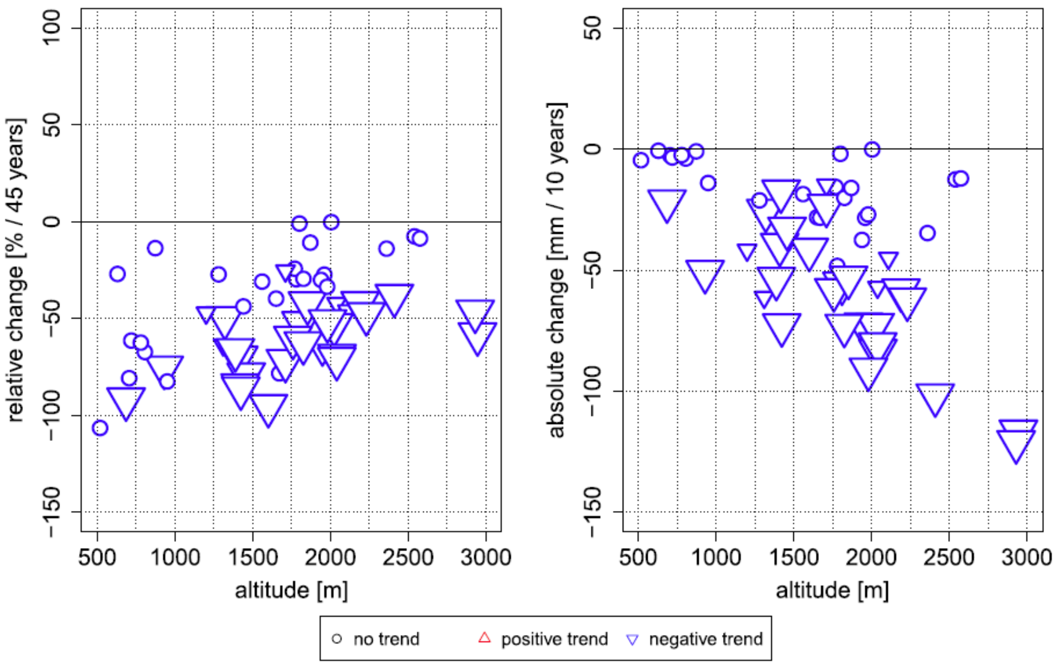

Figure 2-5: April 1 relative (left) and absolute (right) SWE trends (1968–2012) of 54 long-term stations in the Alps as a function of altitude. Large triangles indicate significant trends ($p < 0.05$) and small triangles indicate weakly significant trends ($p < 0.2$). Circles represent stations with no significant trend ($p \geq 0.2$) (adapted from Marty et al. 2017a).

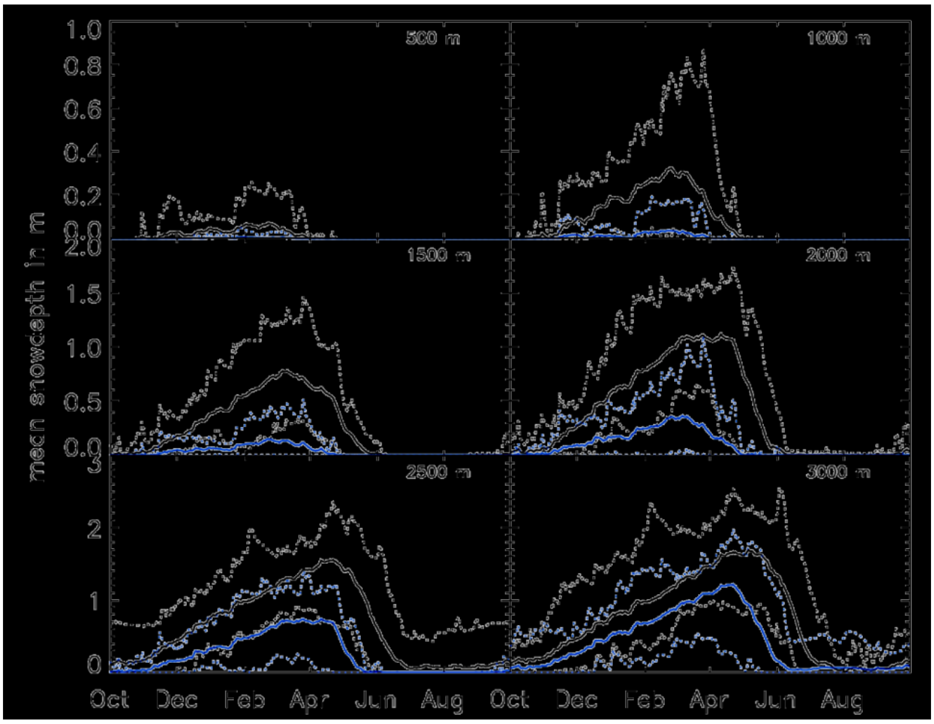

Figure 2-6: Mean (solid), maximum and minimum (dotted) snow depth for the reference period (black) and the A2 scenario (blue) towards the end of the century in the Aare catchment for six elevation zones. The elevation zones are 100m wide, i.e., the 1500m

zone, contains all pixels between 1450 and 1550 m asl. Note that the scale of the y axis changes with elevation (adapted from Marty et al. 2017b).

4. Implications of projected snow changes on Swiss water resources

4.1 Water availability

Challenges already persist in the governance and management of water availability. Climate change impacts are likely to exacerbate these issues, by introducing an extra layer of uncertainty and shifting the hydrological baselines upon which rules and policies are based for different scales and sectors (Clarvis et al. 2014). Most ski resorts invested millions of Swiss francs in the last two decades in a network of machines to produce technical snow along their kilometre long ski runs in order to gain a competitive advantage and to be prepared for snow poor winters. Such a network requires vast of water either from artificial reservoirs on the mountain slopes or from rivers or lakes in the valleys. This water is needed in times when natural flow is already on its lowest level and when Alpine winter tourist areas have the highest demand. This is due to both artificial snow production and the doubled or tripled number of people during the Christmas/New Year holidays. After a dry fall such situation have locally already initiated discussions about the correct governance of water use (Schneider et al., 2015). However, this particular problem may become slightly smaller in the future due to an expected increase in winter runoff from Alpine catchments in a warmer climate (Bavay et al. 2013). On the other hand less snow in spring increases the probability for low flows in summer. Such changes in the seasonal availability of water resources can have local and temporal impacts on water management, such as irrigation of residential zones, drinking water or water uses related to tourism (e.g., artificial snow production, irrigation of golf courses) or to agriculture, especially in southwestern Switzerland (Reynard et al. 2014). Although there is no water stress in this region at the moment, it can be assumed that through the general decrease in SWE, less water will be available during summer, where water demand for irrigation is increasing (Jenizek et al. 2018, Etter et al. 2017). However, the size and temporal shift of the seasonal change is highly dependent on the hydrology of the region, i.e. rain-dominated catchments react differently than melt-dominated catchments, especially for extreme flow regimes (Brunner et al. 2019).

4.2 Hydropower production

The increasing production of artificial snow needs not only water, but also power. The necessary water for the snow production often needs to be pumped up from rivers or hydropower reservoirs. Local reservoirs built to store water for snow production or usually too small and have to be filled several times during the early winter. This happens at times when natural river flow is at its lowest level, which together with the demand for hydropower production can cause problems with environmental regulations. The activity can also be cost-intensive, since electricity prices are higher during winter due to generally increased demand in that season. The presence of snow in the Swiss Alps has therefore a direct bearing on the energy sector. This is important in countries like Austria or Switzerland that depend for more than 50 % on hydropower for electricity generation (Romerio 2002). The projected decrease in snow depth and snow duration will drastically reduce the amount of snow mass available for runoff. Accordingly, peak runoff from snow is projected to occur earlier in the season or might even be suppressed in some years. Therefore, it can be assumed that the electricity production through hydropower will be increased during the winter season, but reduced in summer due to the large reduction in snow cover. This implies that runoff is less variable through the year, which may positively affect hydropower. On the other end, the abovementioned reduction in summer runoff implies that some mountain rivers may no longer be able to maintain sustained discharge during prolonged dry spells (Addor et al. 2014; Köplin et al. 2014).

4.3 Natural hazards and other impacts

The above-mentioned intensification of snowmelt, the increase in rain events, and the general decrease in snow depth and snow duration will probably affect the frequency, number and seasonality of landslide activations and debris flows (Stoffel et al. 2014). Moreover, rapidly melting snow can, in the presence of heavy rainfall, provide significant amounts of water that converge towards mountain torrents and their tributaries, leading to floods in some instances (Stoffel and Corona 2018). The future frequency and intensity of hazardous runoff from rain-on-snow events is uncertain (Wuerzer and Jonas, 2018), but according to Beniston and Stoffel (2016) rain-on-snow may increase in future despite a generally reduced snow cover as long as the warming does not go beyond +4 degrees. The same processes may also enhance the risk for wet snow avalanches (Pielmeier et al. 2013). Moreover, more frequent and especially more intensive winter rainfall will probably increase the risk for mixed avalanches. These are avalanches which may start as a power snow avalanche on the top of mountain and end as a mixture of a wet snow avalanche and a debris- or mud flow in the valley ground. This type of avalanches often constitutes a problem since the amount of water reduces the friction, which can dramatically increase the runout distance of the avalanche. On the other end, the projected decrease in the number of days with snowfall will reduce cost for snow removal of transportation infrastructure (Figure 2-7), for road accidents, for airport and road closures.

Other well-known impacts comprise winter tourism, which is the main economic sector in many Alpine valleys. This business is among others impacted by climate change, i.e., heavily dependent on snow (Gonseth 2013). Ski resorts are highly affected by the projected decrease in snow depth and snow duration, since the absence of enough natural snow needs to be compensated through the production of artificial snow (Figure 2-8). Besides being highly temperature dependent, this also implies higher water consumption, and is very cost-intensive (Abegg 2013). It can be assumed that the small ski resorts at mid elevations, which are already endangered today, will disappear. The remaining resorts are projected to experience a non-continuous snow cover at least every second winter. The strong decrease in snow duration, i.e. the earlier snow disappearance may also changes the visual appearance of the mountains during summer and thus heavily influencing the “Alpine landscape” perception.. For example, the typical summer tourist picture, snow covered peaks in front of green meadow, may become hard to get after a few hot weeks in a future summer.,

A shorter snow duration, especially in spring and summer also heavily influences the glacier melting and the permafrost warming (Huss et al. 2017), because the reflecting surface of the snow cover cannot anymore protect against the strong summer sun (see glacier- or permafrost chapter, respectively). Even flora and fauna do not necessary profit from a longer snow free period (Ragora et al. 2018, Penczykowski et al. 2016). Some species need the snow to protect themselves from freezing temperatures or to hide from predators. Some species may be able to migrate to higher ground others may become extinct due to their too slow reaction or due to a missing appropriate habitat.

Take-home messages

Future declining snow water resources in combination with dry summer periods can locally and temporarily limit the water availability towards the end of the century. However, improved governance and management of the available water can largely mitigate the impact of such situations.

Hydropower production will be mainly affected by changes in seasonality. Due to a shift in water availability, production revenue may increase during the rainier winter months and decrease during the drier summer months.

Snow cover decline will also have other important consequences, such as negative effects on winter tourism or a possible increase in wet snow avalanches. But there are also positive effects like reduced cost for winter road maintenance, less snow induced traffic interruptions or road accidents.

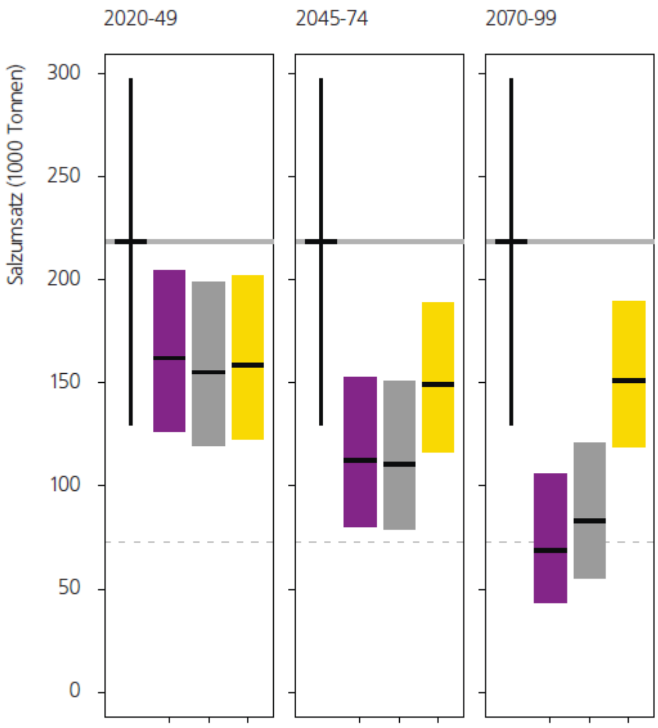

Figure 2-7: Annual mean de-icing salt consumption in Switzerland for the reference period 1997-2012 and its 50 % range (black), and the three future periods 2020-49, 2045-74 and 2070-99 with different emission scenarios (colored). The impact of the A1B (violet), A2 (grey) and the RCP3PD (yellow) scenario are given from left to right (adapted from Zubler et al. 2015).

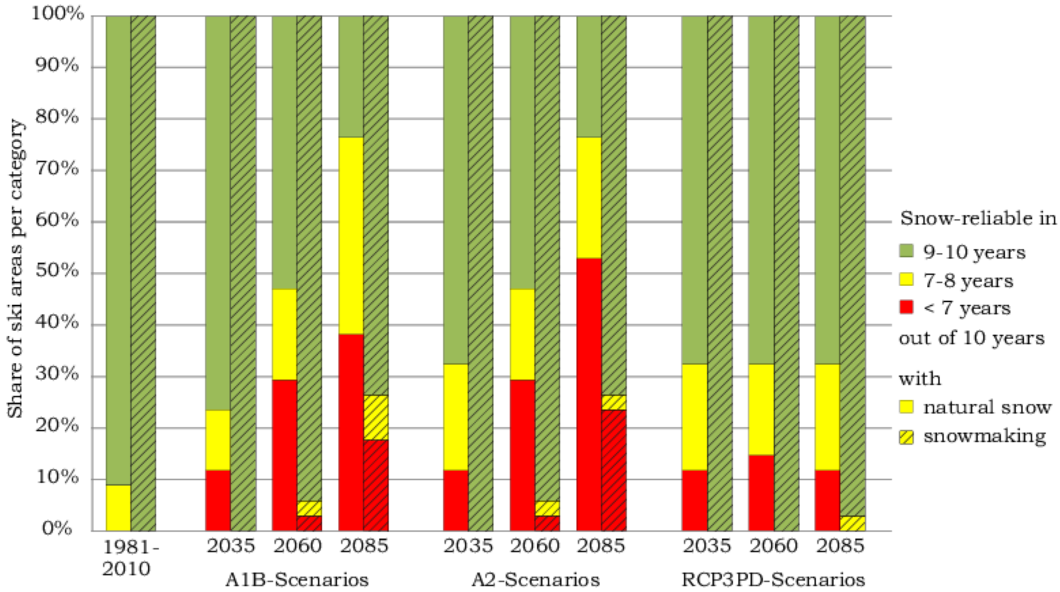

Figure 2-8: Ratio of snow reliable ski areas in Kanton Graubünden. The left bar for natural snow, the right hatched bar in the case of technical snow production. The current situation (left) is shown for the reference period (1981-2010) and the future situation is illustrated for three different time periods and emission scenarios.A ski area is defined to be snow reliable if there are at least 100 days with a minimum snow depth of 30 cm between December 1 and April 15 (adapted from Abegg 2013)

5. Research gaps and open questions

Despite the progress in modelling and remote sensing, observational evidence and monitoring is still an essential part for the process understanding, the model development and the remote sensing data validation. However, there are still some major challenges regarding in-situ observation: The amount of snowfall, for example, can still only be measured automatically in a precipitation gauge.

Current estimate of solid precipitation are also affected by the lack of long-term data series (Hess et al. 2014) and large uncertainties at high elevation. These uncertainties mainly arise from two facts: The low number of precipitation gauges at high elevation and the large bias in observations due to wind-induced under-catch (Kochendorfer et al. 2017). Moreover, measuring solid precipitation with precipitation gauges does not allow distinguishing between solid and fluid precipitation, which make the method of limited use in all cases where rainfall can be expected in winter. Another important variable, which is still a challenge to measure accurately, is the available SWE. Manual in-situ measurements are cumbersome and automatic measurements have a relative high uncertainty depending on the amount and type of snow and the humidity of the ground underneath. The ideal alternative to measure SWE from space is so far also not a solution as current operational satellite SWE retrievals have high uncertainty in case of wet snow and provide estimates at about 25-km resolution only. Hence they are of very limited value in mountain areas with complex topography.

Large uncertainties also exist in the spatial and temporal distribution of precipitation. The spatial distribution, in fact, is not only determined by synoptic systems, but is also strongly affected by topography (Gruenewald et al. 2010). For snow, post-depositional transport such as creep, saltation, suspension, and avalanching additionally influence the spatial distribution.

Recent progress in measuring snow distribution in mountains with remote sensing methods has allowed for a better understanding of typical distribution patterns of alpine snow water resources (Grunewald et al. 2014), as well as for quantifying respective precipitation amounts (Mott et al. 2014). The results have highlighted, however, that even in highly instrumented mountain ranges such as the Alps, total precipitation is still very poorly quantified. The combination of weather modelling with advanced data assimilation techniques, including precipitation radar data, will lead to a more complete understanding of precipitation amounts and types in high mountains, and this is urgently required if future changes in precipitation are to be projected correctly. In this respect, climate modelling is called for continuing the efforts towards increased model resolution.

Several points need to be considered when aiming at an improvement of future projections for snow water discharge: The most important one is the reduction of the uncertainties originating from the precipitation projections. Related to that is a better knowledge about the change in the frequency and intensity of extreme events, which play an important role for the correct representation of avalanche hazard and snowmelt contributed flooding. Another challenge is still the snow modelling. For the modelling of hydrological applications, the catchment scale is the most relevant one (Kumar et al., 2013). Snow models of different complexity are used for this (Magnusson et al., 2015), and principal challenges are (a) to distinguish between uncertainties introduced by the model structure and uncertainties related to the input data (Schlögl et al., 2016), and (b) to develop transferable, site-independent model formulations without the need of calibration. The latter is particularly important for reliable predictions of climate change effects (Bavay et al., 2013) and for model applications to ungauged catchments (Parajka et al., 2013). Another unsolved challenge so far is the fact that the often-used statistical downscaling of climate model projections destroys the physical consistency among the meteorological variables, which is an important prerequisite for energy balance based snow models. Moreover, snow modelling in Alpine catchments is virtually always influenced by the large share of forest cover. Snowmelt in forest environments substantially influences the timing of spring surface runoff and largely contributes to the total runoff. The understanding of interactions between forested environments and seasonal snow cover is therefore important for accurate snowmelt predictions. The modelling of these processes, including the influence of canopy shading on effective albedo, is still in development (Webster and Jonas., 2018) and so far remains another large source of uncertainty in the representation of Alpine snow water resources.

Take-home messages

Open challenges in the hydrology of snow-dominated catchments can be divided into three research lines:

(1) Climate models: Decreasing the uncertainty associated with future projections of precipitation and developing downscaling processes that produce physically-consistent meteorological forcing for snow models.

(2) Parameterizations: Adding new or improving existing parameterizations of poorly-understood processes such as (i) the spatial distribution of snow fall, (ii) the snow redistribution of snow on the ground, or (iii) snow and forest interactions.

(3) Observations: Improving the possibility to automatically distinguish the amount of solid and fluid precipitation and to reliably determine the spatial distribution of SWE from space even over a complex topography like the Alps.

6. Translating research findings into policy-relevant messages

Snow influences life and society in an Alpine country like Switzerland in many ways. The amount and duration of snow in the Alps has a high economic significance in terms of tourism and hydropower. Due to high year to year variability of the Alpine snow cover the rate of snow cover decrease in the Alps is much less clear compared to the rate of glacier retreat. In Switzerland, the close cooperation between public offices and academia during the last few years has played a key role in generating knowledge about projected snow changes and its consequences for hydrology. The efforts preceding the CH2014-Impacts report generated a large body of research around these topics. Advances achieved in the field after 2014 have been reviewed in this report and placed in the context of the previous work. The main findings can be summarized as follows:

- Observations during the last 8 decades demonstrate that snow pack did not change linearly, but more in a step wise manner after the end of the 1980's. Some recovery towards more normal snow conditions during the last decade can only be observed above 1300 m asl.
- Towards the end of the century a multi-day snow cover is projected to become a rare phenomenon in the Swiss plateau, whereas snow depth and duration will be significantly reduced at mid elevations. The projected strong warming will also cause a clear decrease of the snowpack in mountainous regions. The major signal of change is an increase in snow melt at very high elevations (>3000 m) in the months of April and May due to the earlier start of snow melting (5–10 days). In addition, the already observed shift from solid (snow) to liquid (rain) precipitation is expected to impact also higher elevations, which would increase the risk for mixed flow avalanches and debris flows in the Alps and mudslides and floods in the lowlands.
- With respect to the hydrological cycle, river runoff regimes in non-glaciated catchments are projected to shift from snow-controlled to rain-controlled under climate change. Winter discharge is projected to increase at the expense of decreasing summer discharge. The reason lies, besides the general precipitation increases (decreases) projected for winter (summer), in projected changes in the cryosphere, i.e. the general increase in liquid precipitation and the increased snow melt already in mid-winter.

Based on these considerations, the following messages can be formulated to policy makers and stakeholders:

- The expected increases to runoff particularly in the Alps increase the potential for hydropower electricity generation in the more elevated regions. Seasonally, snow dominated catchments will get more winter and less spring and summer runoff (due to the snow decreases) which is consistent with the evening out of the annual cycle and decreases to spring flood peaks. This may decrease the need for reservoir storage of runoff to meet peak winter energy demands. However, in the lowlands low-runoff situations may become more common.
- In regard to water needs for technical snow production enough reservoirs at high elevation in the ski areas are likely to play an important role in the next few decades in order to be independent of other water users in the valleys. With smart planning such reservoirs and the corresponding network of water pipes can also be used as power producers or for irrigation purposes. Nevertheless, strategies towards more diverse winter tourism to get less dependent on snow-making will be asset in the long-term future.
- The increasing impacts of climate change are requiring governance frameworks and management techniques to develop approaches and adapt to more unpredictable uncertainties and changes. The increasing diversity of future hydro-climatic conditions

(e.g. reduced run-off contribution from snow melt, more rain on snow events or unprecedented avalanche runouts) implies that governance cannot approach the future based only on the variability of the past.

- The continuation of long-term monitoring of Alpine snow resources is a necessity for the development of any future strategy to cope with changing snow conditions and natural hazards given the nonlinearity of the climate system and the limitations of current climate models.

Take-home messages

The close cooperation between public offices and academia has played a key role in generating knowledge about snow changes and its consequences for natural hazards and hydrology.

The projected snow cover decrease has mainly negative effects for winter tourism, but can have also positive effects for power production, since runoff from many Alpine catchments will be seasonally more equally distributed.

While the general patterns and impacts of the snow decrease are clear, uncertainties in climate scenarios and poorly-understood processes, especially regarding extremes and natural hazards will still require policy makers to deal with considerable uncertainties for future projections.

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