Glaciers

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

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Executive summary

Meltwater from Alpine glaciers is a key component of the Swiss hydrological budget: It significantly contributes to total discharge, sustains minimum flow levels during dry periods, and shapes seasonal regimes. Due to climate change, Swiss glaciers are anticipated to lose between 59% and 93% of their 2018 ice volume by 2100. The associated glacier retreat will impact hydrology, ecosystems, sediment transport, water quality, landscapes, and mountain hazards.

Although there is high confidence in the projected general decline in glacier extents and related impacts, the exact trajectory of glacier discharge for individual catchments and regions is still affected by important uncertainties. On the one hand, these derive from the difficulty of accurately projecting future climate; a difficulty linked to both unknown future emissions and internal climate variability. On the other hand, some glacial processes are still poorly understood, and thus insufficiently accounted for in model projections: the spatial distribution of snow accumulation, the long-term evolution of glacier debris cover, the feedback between englacial and subglacial hydrological processes and ice flow, or the influence of newly formed proglacial and ice-dammed lakes on glacier retreat, all need further research.

Further uncertainties linked to the characterisation of the present glacier state, such as the correct quantification of the present-day glacier ice volume or extent, are currently addressed through dedicated initiatives. Similarly, new remote sensing products and monitoring techniques – such as high-resolution satellite imagery, and data retrieved from both unmanned aerial vehicles and seismic sensors – will play an important role in advancing process understanding, and thus enhanced model-based projections.

Future water management strategies for glacierized catchments will need to account for changes in both total annual water availability and hydrological regimes. Such strategies will be of particular importance to tackle critical low-flow conditions during droughts. Due to the intrinsic difficulty in accurately predicting future meltwater contributions, it is important that the related uncertainties will appropriately be accounted for.

Zusammenfassung

Das Schmelzwasser der Alpen-Gletscher ist eine wichtige Komponente des Schweizer Wasserhaushalts: Es trägt wesentlich zum Gesamtabfluss bei, gewährleistet einen Minimalabfluss in Trockenperioden und gestaltet das saisonale Regime. Aufgrund des Klimawandels werden die Schweizer Gletscher bis 2100 voraussichtlich zwischen 59% und 93 % ihres Eisvolumens von 2018 verlieren. Der damit verbundene Rückgang der Gletscher wird Auswirkungen auf die Hydrologie, Ökosysteme, Sedimenttransport, Wasserqualität, Landschaften, sowie Gefahren im Gebirge haben.

Projektionen des allgemeinen Gletscherrückgangs und die damit verbundenen Auswirkungen liefern vollumfänglich übereinstimmende Resultate. Dennoch ist die genaue Entwicklung des Gletscherabflusses für einzelne Einzugsgebiete und Regionen immer noch von erheblichen Unsicherheiten geprägt. Diese ergeben sich zum einen aus der Schwierigkeit, das zukünftige Klima genau zu prognostizieren. Dies hängt sowohl mit den unbekannten zukünftigen Emissionen als auch mit der internen Klimavariabilität zusammen. Zum anderen sind einige glaziologische Prozesse immer noch schlecht verstanden und damit in Modellrechnungen nur unzureichend berücksichtigt: die räumliche Verteilung der Schneeakkumulation, die langfristige Entwicklung der Schuttbedeckung von Gletschern, die Rückkopplung zwischen hydrologischen Prozessen in und unter dem Gletscher und dem Eisfliessen, oder der Einfluss neuer proglazialer und durch Eis gestauter Seen auf den Gletscherrückzug bedarf weiterer Untersuchungen.

Weitere Unsicherheiten, die mit der Charakterisierung des gegenwärtigen Gletscherzustands verbunden sind – wie zum Beispiel die Quantifizierung des heutigen Gletschereisvolumens und -Fläche – werden derzeit durch gezielte Initiativen angegangen. Ebenso werden neue Fernerkundungsprodukte und Überwachungstechniken, z.B. hochauflösende Satellitenbilder und Daten, die sowohl von Drohnen, wie auch von seismischen Sensoren aufgenommen werden, eine wichtige Rolle für das Prozessverständnis und damit die Verbesserung von modellbasierten Projektionen spielen.

Zukünftige Strategien für die Bewirtschaftung von Wasser aus vergletscherten Einzugsgebieten werden sowohl die Änderungen in der jährlichen Wasserverfügbarkeit, als auch der hydrologischen Bedingungen berücksichtigen müssen. Solche Strategien werden vor allem bei Niedrigwasser während Dürren von Bedeutung sein. Aufgrund der intrinsischen Schwierigkeit, zukünftige Schmelzwasserbeiträge genau vorherzusagen, ist es wichtig, dass die damit verbundenen Unsicherheiten angemessen berücksichtigt werden.

Résumé

L'eau de fonte des glaciers alpins est un élément clé du budget hydrologique de la Suisse: elle contribue de manière significative au débit total, elle maintient des niveaux d'écoulement minimum pendant des périodes sèches et façonne les régimes saisonniers. En raison du changement climatique, les glaciers suisses devraient perdre entre 59% et 93% de leur volume actuel d'ici 2100. Le recul des glaciers aura un impact sur l'hydrologie, les écosystèmes, le transport des sédiments, la qualité de l'eau, les paysages et les dangers naturels en montagne.

Bien qu'il y ait une grande confiance dans le déclin général des glaciers et des impacts associés, la trajectoire exacte du débit des glaciers pour des bassins versants et des régions spécifiques est encore affectée par d'importantes incertitudes. D'une part, ceux-ci sont déterminées de la difficulté de précisément projeter le climat futur. Cette difficulté est liée à la fois aux émissions futures inconnues et à la variabilité interne du climat. D'un autre côté, certains processus glaciaires sont encore mal compris, et donc insuffisamment pris en compte dans les projections des modèles: p.ex. la distribution spatiale de l'accumulation de neige, l'évolution de la couverture de débris supraglaciaire à long terme, la rétroaction entre les processus hydrologiques dans et sous le glacier et le mouvement de la glace, ou l'influence de lacs proglaciaires nouvellement formés sur le retrait des glaciers, ont tous besoin de recherches supplémentaires.

D'autres incertitudes liées à la caractérisation de l'état actuel des glaciers, telles que la quantification du volume ou de la surface actuellement couverte de glace, sont traitées par de diverses initiatives spécifiques. De même, de nouveaux produits de télédétection et de nouvelles techniques de surveillance – comme l'imagerie satellitaire à haute résolution et des données récupérées par des drones ou des capteurs sismiques – joueront un rôle important pour avancer la compréhension des processus, et donc des projections basées sur des modèles plus détaillées.

Les stratégies de gestion de l'eau pour les bassins versants glaciaires devront tenir compte des changements futures dans la disponibilité en eau totale et les régimes hydrologiques. Ces stratégies seront particulièrement importantes pour faire face aux conditions critiques pendant des sécheresses. En raison de la difficulté inévitable de précisément prévoir les contributions futures des eaux de fonte, il est absolument nécessaire que les incertitudes associées soient correctement prises en compte.

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List of abbreviations

AAR (technical term): Accumulation-Area Ratio.
ACQWA (project): Assessing Climate Impacts on the Quantity and quality of Water.
ASTER (satellite): Advanced Space-borne Thermal Emission and Reflection Radiometer.
asl: above sea level
BC: Black Carbon.
CCHydro (project): Climate Change and Hydrology in Switzerland.
CHR (institution): International Commission for the Hydrology of the Rhine basin.
CHy (institution): Swiss Hydrological Commission.
CORDEX (project): Coordinated Regional Climate Downscaling Experiment.
CO2: Carbon Dioxide.
CTI (institution): Commission for Technology and Innovation.
DEM (technical term): Digital Elevation Model.
DETEC (institution): Federal Department of the Environment, Transport, Energy and Communications.
ELA (technical term): Equilibrium Line Altitude.
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.
GLOF (technical term): Glacier Lake Outburst Flood.
InSAR (method): Interpherometric Synthetic-Aperture Radar.
ISI (institution): Institute for Scientific Information.
LIA (period): Little Ice Age.
LIDAR (method): Light Detection And Ranging.
MODIS (satellite): Moderate Resolution Imaging Spectroradiometer.
MSI (method): MultiSpectral Instrument.
NCCR Climate (institution): National Centre of Competence in Research "Climate Variability, Predictability and Climate Risks".
NCCS (institution): National Centre for Climate Services.
NELAK (project): New lakes in deglaciating high-mountain areas: climate-related development and challenges for sustainable use.
OCCR (institution): Oeschger Centre for Climate Change Research.
OLI (method): Operational Land Imager.
PREVAH (model): PREecipitation-Runoff-EVApotranspiration HRU Model.
RCP (technical term): Representative Concentration Pathways.
RGI (dataset): Randolph Glacier Inventory.
SCCER-SoE (institution): Swiss Competence Centre for Energy Research, Supply of Electricity.
SGHL (institution): Schweizerische Gesellschaft für Hydrologie und Limnologie.
SGI (dataset): Swiss Glacier Inventory.
SNSF (institution): Swiss National Science Foundation.
SRTM (satellite): Shuttle Radar Topography Mission.
TOPKAPI (model): TOPographic Kinematic APproximation and Integration.
UAV (technical term): Unmanned Aerial Vehicles.
w.e. (technical term): water equivalent.

1. Introduction

1.1 The hydrological role of glaciers in Switzerland

Water discharge from glacierized areas provides a significant and essential runoff contribution to the headwaters of Swiss Alpine rivers. At the national scale, glaciers represent the largest water reservoir after groundwater (~150 km^3) and lakes (~130 km^3) (FOEN, 2012). In 2010, for which the last Swiss Glacier Inventory (SGI) is available (Fischer et al., 2014), there was a total of 1420 glaciers in Switzerland, covering an area of 944.3 ± 24.5 km^2 and having an estimated ice volume of 59.9 ± 5.5 km^3 (Fischer et al., 2015) ([1]). Updated estimates for 2017 based on the method by Huss and Farinotti (2012) yield an ice volume of about 53.0 ± 4.9 km^3. Using a typical value of 900 kg m^{-3} for glacier ice density, this volume corresponds to 47.7 ± 4.4 km^3 of water equivalent (w.e.).

In low-elevation areas, runoff generation is mostly driven by rain and seasonal snowmelt. In comparison, ice melt in Switzerland can represent a large share of streamflow and dominates 5 of the 16 typical Swiss hydrological regimes (Aschwanden et al., 1983; Weingartner and Aschwanden, 1992). Ice-melt dominated regimes are characterized by maximum discharge around August, and minimum flows during winter. The runoff share of ice melt varies depending on climate and the size of the glacierized areas, among others. It is particularly relevant during late summer, when the seasonal snow cover has been depleted and precipitation is limited, and during droughts. In Switzerland, ice melt contribution to runoff can be important even for locations relatively far away from glaciers, although with large differences between sites. Between 1988 and 2008, the average glacier contribution to runoff during August to major Swiss rivers varied between 2.5% at Bellinzona (Ticino), and 46.8% at Chancy (Rhone) (Huss, 2011).

1.2 Hydrological impacts of glacier retreat in response to climate change

Most glaciers on Earth have retreated since the end of the Little Ice Age, which for the European Alps ended around 1850. Numerous glaciological observations have produced conclusive evidence that the retreat has accelerated during the last decades, reaching the highest rates since the beginning of continuous monitoring programs in the 1950s (Vaughan et al., 2013; Zemp et al., 2015, 2019). The observed glacier retreat is consistent with the unequivocal warming of the climate system caused by the anthropogenic increase in greenhouse gas concentrations (IPCC, 2013). There is also growing evidence that warming is occurring more rapidly in high-mountain environments than at lower elevations (Pepin et al., 2015). Mechanisms proposed to explain this observation include the snowline-retreat to higher altitude and the related albedo-feedback, as well as changes in radiative and latent heat fluxes resulting from changes in water vapour content, and aerosol deposition (for deteils, refer to Pepin et al., 2015). As air temperature increase has brought most glaciers out of balance, glaciers would continue to retreat even if climate was to remain stable (Mernild et al, 2013; Vaughan et al, 2013; Zemp et al, 2015), especially large glaciers with long response times (Jouvet et al., 2019; Zekollari and Huybrechts, 2015). This glacier retreat is often referred to as the “committed ice loss”.

In regions where glacier meltwater significantly contributes to catchment runoff, the expected reductions in ice volume can highly impact the water budget and hydrological seasonality. These anticipated changes will potentially decrease water security in the long term. For any particular glacier, this process is expected to occur in two stages: Initially, the air temperature

[1] Uncertainties are derived from those calculated by Huss and Farinotti (2012) for Central Europe.

increase will cause enhanced ablation, thus leading to a transitory increase in annual discharge. In the long term, however, and once the glacier has significantly shrunk, discharge will decrease due to the reduced ice volume that is available for melt (Jansson et al., 2003; Huss et al., 2008; Bliss et al., 2014). In Switzerland, trend analyses of streamflow records (Birsan et al., 2005; Pellicciotti et al., 2010) and modelling results from glacier-runoff models (Salzmann et al., 2012; Farinotti et al., 2012) are consistent with this pattern. Figure 1.1 presents a summary of the current runoff trends for Swiss glaciers, based on the results of the Global Glacier Evolution Model by Huss and Hock (2015, 2018).

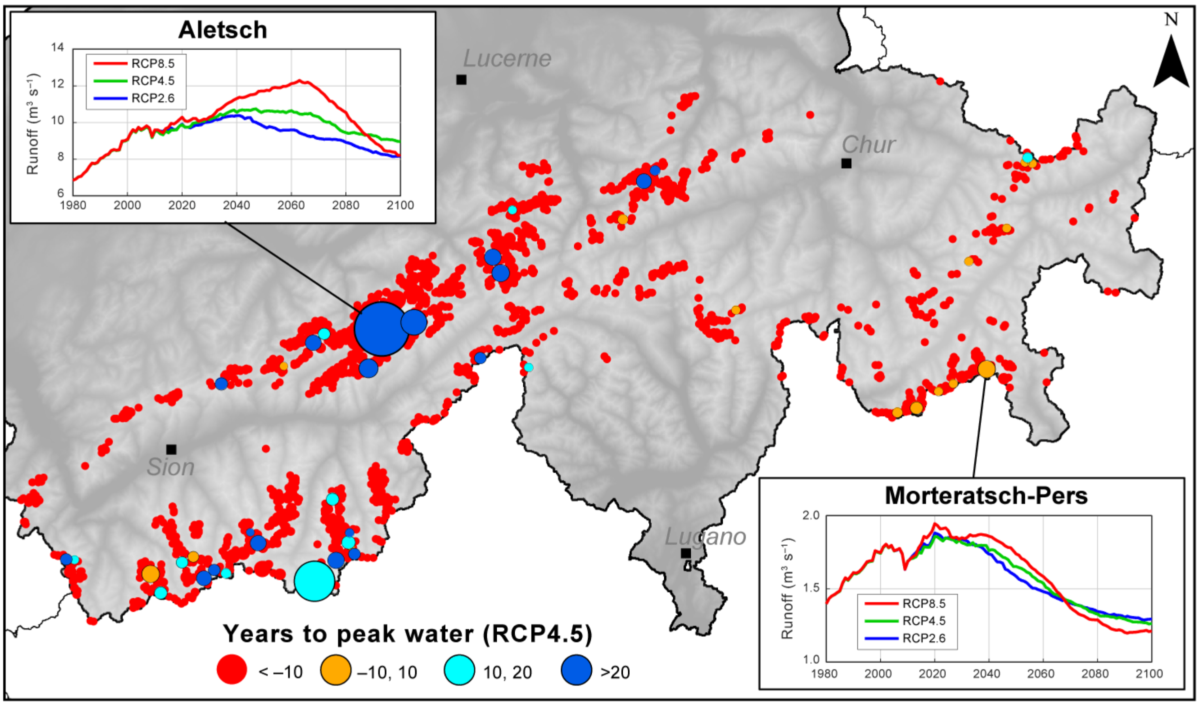

Figure 1.1: Timing of "peak water" for Swiss glaciers. The colour of the dots represents the number of years from (negative values) or to (positive values) the maximum annual runoff contribution. The size of the dots represents today's glacier surface area. Examples of the temporal trends for Grosser Aletschgletscher and Morteratsch-Pers glaciers are given in the two subpanels (time series correspond to 10-years moving averages of average annual runoff). The figure refers to RCP4.5 and is based on results from Huss and Hock (2018).

Current estimates of the ice volume stored in Swiss Glaciers at the end of the Little Ice Age are about 130 km^3 (using the method by Huss and Farinotti, 2012), which would mean that glaciers have lost about 60% of the volume they had in the 1850s. As glacier mass loss progresses, the influence on hydrological regimes becomes more marked. The almost complete disappearance of glacial hydrological regimes is one of the expected consequences of climate change. These regimes will gradually shift to regimes that are more typical for lower elevations, where maximum flows occur during winter or spring (Köplin et al., 2012; Addor et al., 2014). In general, a stronger dependence of summer runoff on seasonal precipitation, and minimum flows smaller than those observed at present, are consequences to be anticipated (Bliss et al., 2014; Huss and Hock, 2018). Without glacier discharge, river headwaters will be more exposed to the seasonal and inter-annual variability of precipitation (Jansson et al., 2003; Viviroli et al., 2011).

Expected changes in the water budget and seasonality may impact water provision for human consumption, ecosystems, agriculture and industry (Beniston and Stoffel, 2014; Huss et al., 2017; Beniston et al., 2018). Furthermore, glacier retreat can increase glacier-related hazards, such as the appearance and extension of proglacial lakes (Haeberli et al., 2016; Magnin et al., 2020) or enhanced activity of mountain mass movements (Stoffel et al., 2014; Haeberli et al., 2017) and sediment transport (Hallet et al., 1996). Additional impacts associated with landscape changes, nutrient flux, water quality, aquatic habitat and biotic communities might also be expected (Huss et al., 2017; Beniston et al., 2018).

1.3 Objectives of this chapter

The above context shows that future projections of glacier ice volume and discharge are essential for the long-term planning of water supply and management in Switzerland. Despite the large progress in the modelling of glacier evolution and hydrology during the last two decades, several research questions still need to be tackled to provide reliable projections. This chapter will summarize the advances that have been achieved since the publication of the CH2014-Impacts (2014) report and discusses possible avenues of future research.

The next section (Section 2) summarizes past and ongoing projects addressing past and future changes of Swiss glaciers and their runoff contribution. In Section 3, the most recent advances in glacio-hydrological studies are reviewed, notably including results that have emerged after the release of the new CH2018 climate scenarios (CH2018, 2018). Individual sub-sections are dedicated to modelling studies (Section 3.1), new monitoring techniques (Section 3.2), and a case study at Findelengletscher, Valais (Section 3.3). The implications of these results on Swiss water resources are discussed in Section 4. Sections 5 and 6 outline open research questions and provide conclusions with a special focus on policy-relevant messages.

Take-home messages

With a total area of about 900 km^2 and an estimated ice volume of 53 km^3 (in 2017), glaciers represent a large water reservoir in Switzerland. Glacier meltwater provides a significant contribution to runoff, shapes hydrological regimes, and decreases inter-annual and seasonal variability by sustaining minimum water levels during summers and droughts.

Since 1850, Swiss glaciers have retreated in response to the warming of the global climate system. Projected future reductions in glacier runoff will modify annual water budgets and hydrological seasonality, potentially impacting water supply for human consumption, ecosystems, agriculture, industry and hydropower generation. Without glacier discharge, river headwaters will be more exposed to the seasonal and inter-annual variability of precipitation.

This chapter reviews recent advances in the capabilities of projecting future glacier changes and related hydrological impacts.

2. Recent projects and initiatives assessing the impacts of glacier retreat on water resources

In the last decade, several public agencies, associations, companies, universities and research centres have cooperated to study the impacts of climate change in Switzerland. The effects in terms of glacier evolution and hydrology have often been considered. In Section 2.1, the outcomes of six major projects are revised (Table 2.1) whilst Section 2.2 outlines some recent and ongoing initiatives, including their expected results.

2.1 Review of past initiatives

The different factors that will affect Swiss hydropower production in the next decades were the focus of the project "Auswirkungen der Klimaänderung auf die Wasserkraftnutzung" ("Impacts of climate change on hydropower", in German), coordinated by the Swiss Hydrological and Limnological Society (SGHL) and the Swiss Hydrological Commission (CHy) (2011). Results of the SGHL-CHy project show that in the high-elevation areas of South and East Valais, the impacts of climate change on hydropower generation are likely to be small in the near future (i.e. until 2035), but that a decrease between 4 and 8% can be expected in the long-term (2085) due to the anticipated glacier retreat and changes in the hydrological seasonality. Uncertainties in the order of 10% were estimated for the near future but these are likely becoming larger in the long term. In relation to past periods, the authors report that several stream gauges at highly-glacierized catchments showed an increase of annual discharge in response to warmer temperatures. At the Gornera streamflow gauge (2007 m above sea level (asl), ~63% glacierized), for example, an increase of about 30% of annual runoff was observed for the period 1968-2008. The impacts of glacier retreat were analysed based on the results from two independent studies (VAW, 2011; Paul et al., 2011). VAW (2011) used the process-based Glacier Evolution and Runoff Model (GERM; Huss et al., 2008; Farinotti et al., 2012) to simulate glacier evolution and water discharge for both Gornergletscher and the catchment of the Mattmark dam, during the period 1900-2100. About 21% of the current ice volume of Gornergletscher and the Mattmark catchment will remain by 2100. In a second study, Paul et al. (2011) simulated the evolution of all glaciers in Switzerland using an empirical relation between glacier size and steady-state accumulation area ratio (AAR) (Paul et al., 2007). By 2100, and assuming the A1B scenario, Swiss glaciers will retain only about 25% of their current volume, with an uncertainty of about 30%. The results by Paul et al. (2011) also suggested that nearly 500 new lakes may form in the Swiss Alps, occupying a total area of 50 km^2 and a total volume of 2 km^3. The latter is equivalent to about half the volume currently stored in all Swiss dams. These lakes can represent an interesting opportunity for hydropower generation, and could have similar effects as glaciers in terms of water storage reserves. Whether a particular site is suitable or not for water resources regulation will depend on local features, such as the surrounding topography, access, and sediment influx. Negative consequences can be expected as well. The formation of proglacial lakes can, for example, cause accelerated glacier retreat due to frontal melt and calving, or increase the risk of Glacier Lake Outburst Floods (GLOFs).

ACQWA (http://www.acqwa.ch/) was a large inter-disciplinary project in which the vulnerability of water resources to declining snow and ice due to global warming was assessed (Beniston et al., 2011). To simulate the hydrology of high-elevation catchments, a glacier evolution and runoff model was developed within the ACQWA project (Carenzo, 2012). At the same time, the TOPKAPI-ETH glacio-hydrological model was further advanced (Finger et al., 2011, 2012; Ragettli and Pellicciotti, 2012; Fatichi et al., 2014, 2015). The project produced results for several mountain regions in the world but had a particular focus on the Rhone valley. 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-elevations sites. Changes in the total runoff of the Rhone basin are likely to be small, but local changes

Table 2.11-1: Pre-CH2018 projects including the future evolution and runoff contribution of Swiss glaciers

Project name	Period	Funded by	Online repository	Summary report (reference)
Auswirkungen der Klimaänderung auf die Wasserkraftnutzung[2]	2008-2011	- Swisselectric Research, Bern - Bundesamt für Energie BFE, Bern - Kanton Wallis, Dienststelle für Energie und Wasserkraft DEWK des Kantons Wallis, Sion - Forces Motrices Valaisannes FMV SA, Sion	https://naturwissenschaften.ch/service/publications/52708-auswirkungen-der-klimaaenderung-auf-die-wasserkraftnutzung---synthesebericht	Auswirkungen der Klimaänderung auf die Wasserkraftnutzung – Synthesebericht (SGHL and CHy, 2011)
Assessing Climate impacts on the Quantity and quality of Water (ACQWA)	2008-2013	- 7th framework program for research and innovation of the European Commission	http://www.acqwa.ch/	ACQWA - A Summary for Policymakers (ACQWA, 2013)
Climate Change and Hydrology in Switzerland (CCHydro)	2009-2011	- Federal Office for the Environment (FOEN)	https://www.bafu.admin.ch/bafu/en/home/topics/water/water--publications/publications-water/effects-climate-change-water.html	Effects of climate change on water resources and waters (FOEN, 2012)
Future glacier evolution and consequences for the hydrology (FUGE)	2010-2013	- National Research Programme "Sustainable Water Management" (NRP 61)	http://www.nrp61.ch/en/projects/project-fuge	Different summary products of the NRP 61 and publications published within the FUGE project.
CH2014-Impacts	2011-2014	- Oeschger Centre for Climate Change Research (OCCR, University of Bern) - Federal Office for the Environment (FOEN) - Federal Office of Meteorology and Climatology MeteoSwiss - National Centre of Competence in Research on Climate (NCCR Climate)	http://ch2014-impacts.ch/	Toward quantitative scenarios of climate change impacts in Switzerland (CH2014-Impacts, 2014)
The snow and glacier melt components of the streamflow of the River Rhine and its tributaries considering the influence of climate change[3]	2012-2015	- International Commission for the Hydrology of the Rhine basin (CHR)	http://www.chr-khr.org/en/projects	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)

[2] This project will be referred as SGHL-CHy.
[3] This project will be referred as CHR.

at high-elevation catchments can be very large. The small changes projected for the Rhone basin are mainly a result of the large natural variability of precipitation, which may mask other trends. For the period 2000-2050, high variability in glacier retreat was projected based on the results for six Alpine glaciers (Haut Glacier d'Arolla, Aletsch, Rhone, Gorner, Tsa de la Tsa, and Miage). Debris-free glaciers, moreover, were found to retreat faster than debris-covered glaciers. Interestingly, as small debris-free glaciers might survive for a long time at high-elevation sites, the glacier runoff contribution is expected to gradually diminish.

The main goal of the CCHydro project (FOEN, 2012) was to quantify the impacts of climate change on the hydrology of Switzerland. The cryosphere plays a central role in the key messages of this report. Similar to the conclusions of ACQWA, the authors state that *"there will be little change in the amount of water available up to 2100 (in whole Switzerland). However, as a result of the rise of the snowline associated with increasing air temperature, the volumes of snow and ice stored in the Alps will be greatly reduced"*. It is highlighted that even if current climatic conditions remain stable in the next decades, glaciers will lose about half of their current volume before achieving a new balance. The modelling study conducted for this report applied the GERM model to nine glaciated catchments, containing 40% of the current ice mass in Switzerland (Farinotti et al., 2012). Additionally, the model by Paul et al. (2007) was used to simulate glacier retreat throughout Switzerland (Linsbauer et al., 2012) and used as input for hydrological simulations with the PREVAH model (Bernhard et al., 2011). By 2100, glaciers were found to lose between 60 and 80% of their current area. As most (about 80%) of the glacier ice volume of Switzerland is currently located in the canton of Valais, this will likely be the region with the largest ice remainders by the end of the century. Similarly to the results of SGHL and CHy (2011), the estimates suggested that about 20-30% of the current volume could remain until 2100. Since the studied areas differed considerably in terms of size, altitude and extent of glacierization, it is difficult to generalize results. In relation to streamflow changes, an important statement is that the glacial hydrological regime, which currently dominates several catchments in the Alps, will almost completely disappear in the long term, with the exception of the basin of the River Massa, which contains the Grosser Aletschgletscher. The hydrological regimes of the other sites will gradually be transformed into regimes that are more typical for lower altitudes (e.g. from glacial into nivo-glacial and nival regimes). Since a rise in air temperatures is the clearest effect of climate change, an important conclusion is that the hydrological sensitivity of glacierized catchments to climate change is much larger than that of lower catchments, because the latter are much more affected by precipitation variability.

In the context of the National Research Programme "Sustainable Water Management" (NRP61), the project FUGE was developed by researchers of ETH Zurich and the University of Geneva (http://www.nfp61.ch/en/projects/project-fuge). The main objectives were to provide an assessment of glacier changes in Switzerland until 2100 and their impacts on water resources and hydropower. Several studies were conducted in the project's frame, focusing on a variety of topics including glacier mass balance reconstruction, development and evaluation of snow accumulation and melt models, determination of glacier bed topography, glacier geometry evolution, glacier discharge, and an economic analysis of the impacts of glacier changes on hydropower. Results from this project are very diverse and can be found in several publications (e.g. Lüthi et al., 2010; Farinotti et al., 2012; Gabbi et al., 2012, 2014). Key findings are that an accurate knowledge of the glacier geometry and ice thickness distribution is essential for projections of glacier evolution (Gabbi et al., 2012), that the projected long-term evolution of glacier mass balance can be sensibly affected by melt model selection (Gabbi et al., 2014), and that spatial patterns of snow accumulation over glaciers are similar from one year to the other, even if the total snow amounts differ in individual years (Clemenzi, 2016). These findings highlight the need of coupling glacier mass balance and hydrological models when simulating long-term runoff changes. On the other hand, the economic study in this project concluded that, for catchments exploited for hydropower generation, the expected runoff-changes can be mitigated through changes in reservoir operation and management (Gaudard et al., 2013). In this context it is important to note that the future evolution of electricity prices are the most uncertain variable, and their variations can be larger than the anticipated changes in runoff (Gaudard et al., 2016).

In the CH2014-Impacts report, the broad impacts of climate change on vegetation, hydrology, energy consumption and others were analysed (CH2014-Impacts, 2014). In line with the outcomes of ACQWA and CCHydro, the total annual runoff volume in Switzerland was projected to remain approximatively constant. However, for highly-glacierized catchments, this was found to be partly at the expense of retreating glaciers. The CH2014-Impacts report included a chapter on the "impacts of snow, ice and ski tourism". Here, different models were forced by CH2011 climate scenarios for the evolution of the snow cover, ski area operability, glaciers, and permafrost to quantify the effect of climate change on the Swiss cryosphere. The LV-model (Lüthi, 2009; Lüthi et al., 2010) was used to project the evolution of 50 Swiss glaciers with detailed measurements under the A1B scenario. The model can simulate the future evolution of glacier geometry using two parameters calibrated with past Equilibrium Line Altitude (ELA) observations and length changes. The GERM model was also used to calculate glacier evolution and water discharge. Results of the two models were very similar and projected that under the A1B scenario, between 5% and 25% (median about 12%) of the current ice volume will remain by 2100. These ice volume projections imply stronger reductions than those estimated by the SGHL and CHy (2011) and FOEN (2012) reports, and are more in line with the latest estimates (Farinotti et al., 2016; Huss and Hock, 2018), as well as with a more detailed modelling study for the Grosser Aletschgletscher (Jouvet et al., 2011; note that the glacier represents about 21% of the total ice volume in Switzerland). Using the results from SGI2010 (Fischer et al., 2014), results from CH2014-Impacts imply that about 710 km^2 would become ice-free in the Swiss Alps. Remaining ice masses will be limited to elevations above 3000 m asl, mostly in the western Alps. Results from the GERM model for this dataset have been extrapolated to the entire European Alps and indicate that Alpine glaciers will reduce their areas to values between 4% and 18% of the values observed in 2003 (Huss, 2012).

Uncertainties in the projections of future glacier evolution and water discharge are one of the main pending issues in the results of all projects. These uncertainties are estimated to be between 20 and 30% (FOEN, 2012) and are a result of several research gaps and unknowns. Importantly, large uncertainties originate from future greenhouse gases emission scenarios, and propagate through the global climate models in different temperature trajectories (SGHL and CHy, 2011). Other uncertainties are associated with the estimations of the current ice volume, the downscaling of precipitation to the glacier scale, the use of hydrological parameters calibrated under present conditions, and poorly-understood processes, such as the decline of glacier albedo, the formation of new proglacial lakes, and the evolution of debris-covered areas (FOEN, 2012; ACQWA, 2013). On top of this, natural climatic variability of precipitation can mask some of the projected streamflow trends in Swiss rivers (ACQWA, 2013).

Amongst the most important outcomes of the SGHL and CHy (2011), FOEN (2012) and CH2014-Impacts (2014) reports, were the future projections for the ice volume of the Swiss glaciers. To provide a more updated estimate, Figure 2.1 summarizes the latest results from GloGEM (Huss and Hock, 2015, 2018), which are based on the Randolph Glacier Inventory (RGI) version 6.0. The Figure presents projections for both the glacier ice volume and the total number of glaciers for the period 2003-2100. It can be seen that results for the scenario

RCP4.5 are comparable to the estimates presented in the CH2014-Impacts (2014) report for the scenario A1B.

In the context of climate scenarios, it is worth mentioning that a debate is ongoing about whether some of the routinely-considered scenarios (such as RCP2.6, or scenarios compliant with the 2015 Paris Agreement) are still to be considered as realistic options (Sanderson et al., 2016; van Vuuren et al.,2018; Tokarska and Gillett, 2018). In this sense, projections based upon such scenarios – including the evolution of the ice volume of Alpine glaciers – may be considered as being too optimistic. A recent global-scale study (Marzeion et al., 2018) also showed that, at the global level, the glacier ice loss expected by the end of the century is largely caused by the glaciers' adjustment to current climate. This means that a large part of the future loss is already committed at this stage, and only weakly dependent from future climate scenarios.

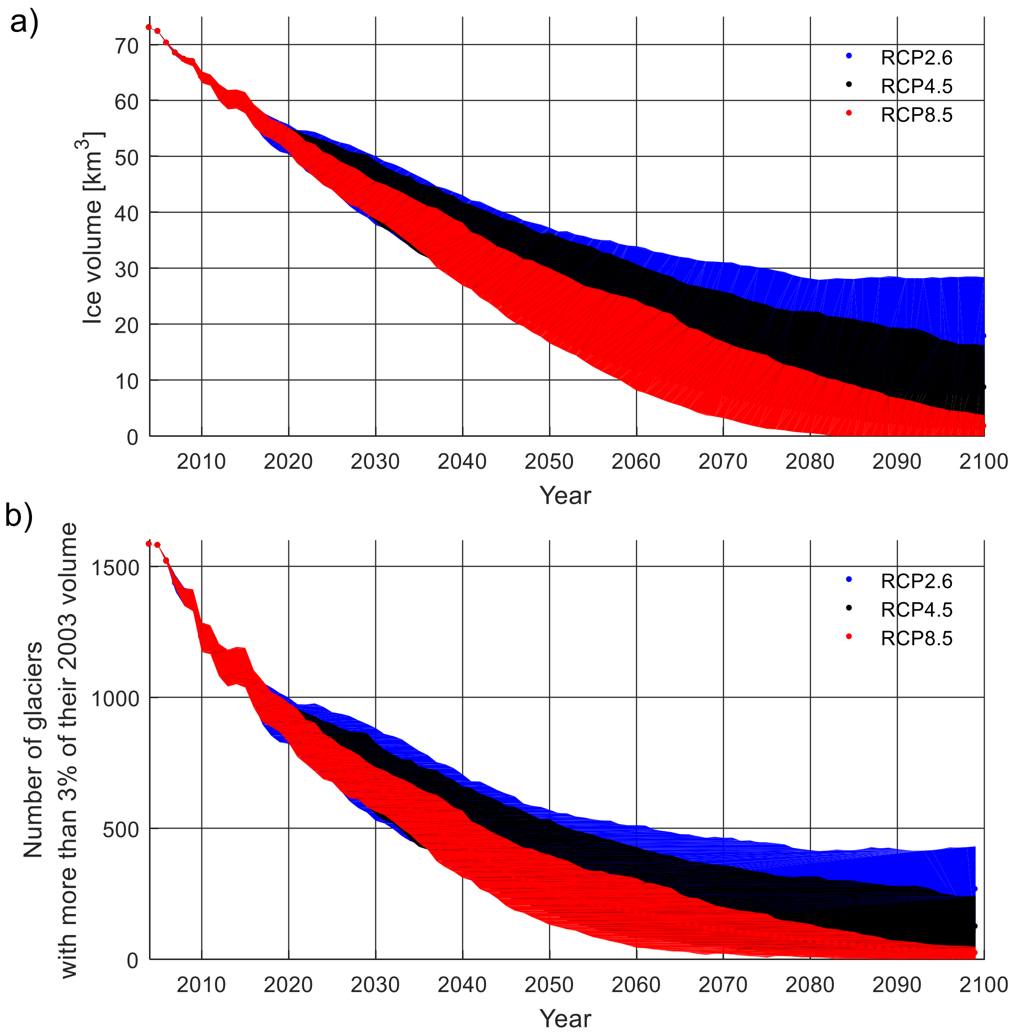

Figure 2.1: The future evolution of Swiss glaciers as calculated by the Global Glacier Evolution Model (Huss and Hock, 2015, 2018) using RGIv6.0. a) Ice volume stored in all Swiss glaciers. b) Number of glaciers in which the ice volume is at least 3% of the one in 2003. Points and uncertainty bands represent the average and the standard deviation, respectively, as calculated from an ensemble of 14 GCMs and emission scenarios RCP2.6, RCP4.5 and RCP8.5. For the three scenarios, the ice volume remaining by 2100 is estimated to be 24%, 12% and 2%, respectively (2003 baseline).

The number of remaining glaciers is 266, 123 and 22, respectively. Alpine-wide results obtained with a model accounting for ice flow dynamics (Zekollari et al., 2019) are shown in Figure 2.3.

After the publication of the CH2014-Impacts report, the International Commission for the Hydrology of the Rhine basin (CHR) coordinated the project "The snow and glacier melt components of streamflow of the river Rhine and its tributaries considering the influence of climate change" (http://www.chr-khr.org/en/projects; Stahl et al., 2016, 2017). In that project, detailed simulations of the hydrology of the Rhine River basin from 1901 to 2006 were performed. The work used a model chain in which glacierized headwater catchments were simulated using the HBV-light hydrological model (Seibert and Vis, 2012). Rain, snowmelt and ice melt contributions to runoff were simulated explicitly. It was found that the ice melt runoff-share at the catchment scale experienced a modest change throughout the 20th century, likely due to a compensation between increasing runoff due to enhanced ablation and decreasing ice volumes due to glacier retreat. The importance of snowmelt along the Rhine River was emphasized in this study.

One of the novel contributions in the CHR project is the explicit quantification of the contribution of ice melt during extreme low flows (Stahl et al, 2017). The authors focused on late summer periods with reduced precipitation and high temperatures, particularly focusing on the years 1921, 1947, and 2003. Ice melt represented up to one third of the discharge measured in Basel and up to one fifth of that measured in Lobith on individual days of August (Figure 2.2). These estimates are similar to those from Huss (2011), who estimated that ice melt contributed to 14.3% of the monthly mean runoff at Lobith in August 2003. The report also suggested that the hydrological impacts of low flow events, such as that of summer 2003, would have been mitigated by a larger glacier extent, such as that present in the early 20th century. Finally, it highlights that uncertainty in future glacier discharge is one of the main issues to be solved in future research. One open question is, for example, at which point during the 21st century the anticipated reduction of ice melt contribution will be clearly noticeable in summer runoff.

2.3 Recent and ongoing initiatives

New climate scenarios for Switzerland were produced within the CH2018 initiative (http://www.ch2018.ch), launched by the National Centre for Climate Services (NCCS). The new set of scenarios were released in November 2018 and now provide the standard input variables for climate change studies in Switzerland – including those addressing glacier changes and related impacts. The CH2018 scenarios replaced those produced for the CH2011 initiative, and are be based on simulations from the European branch of the Coordinated Regional Climate Downscaling Experiment (EURO-CORDEX; Jacob et al., 2014). In comparison to CH2011, the CH2018 scenarios have a higher spatial resolution (2x2km grids, compared to macroscale climatic regions), provide a larger number of simulations (derived from a total of 23 different climate model chains), and are based on a more sophisticated approach for the spatial downscaling (quantile mapping, compared to delta-change approach; CH2018, 2018). The CH2018 scenarios – as well as the EURO-CORDEX climate data from which they were derived – have already been used in hydro-glaciological studies (e.g. Jouvet and Huss, 2019; Brunner et al., 2019a,b; Zekollari et al., 2019) and are expected to impact glaciological research further, e.g. by increasing the confidence in the simulations of transient time series, of inter-annual and diurnal variability, or of extreme events.

Amongst the most prominent glacier-related works that have emerged from the above, are the simulations of past and future glacier evolution presented by Zekollari et al. (2019). The study is based on the EURO-CORDEX climate model ensemble and presented, for the first time, an Alpine-wide simulation that takes ice-flow dynamics explicitly into account. The results consider the three emission scenarios RCP2.6, RCP4.5 and RCP8.5, and anticipate that by the end of the 21st century, the total volume of all glaciers in the Alps will have

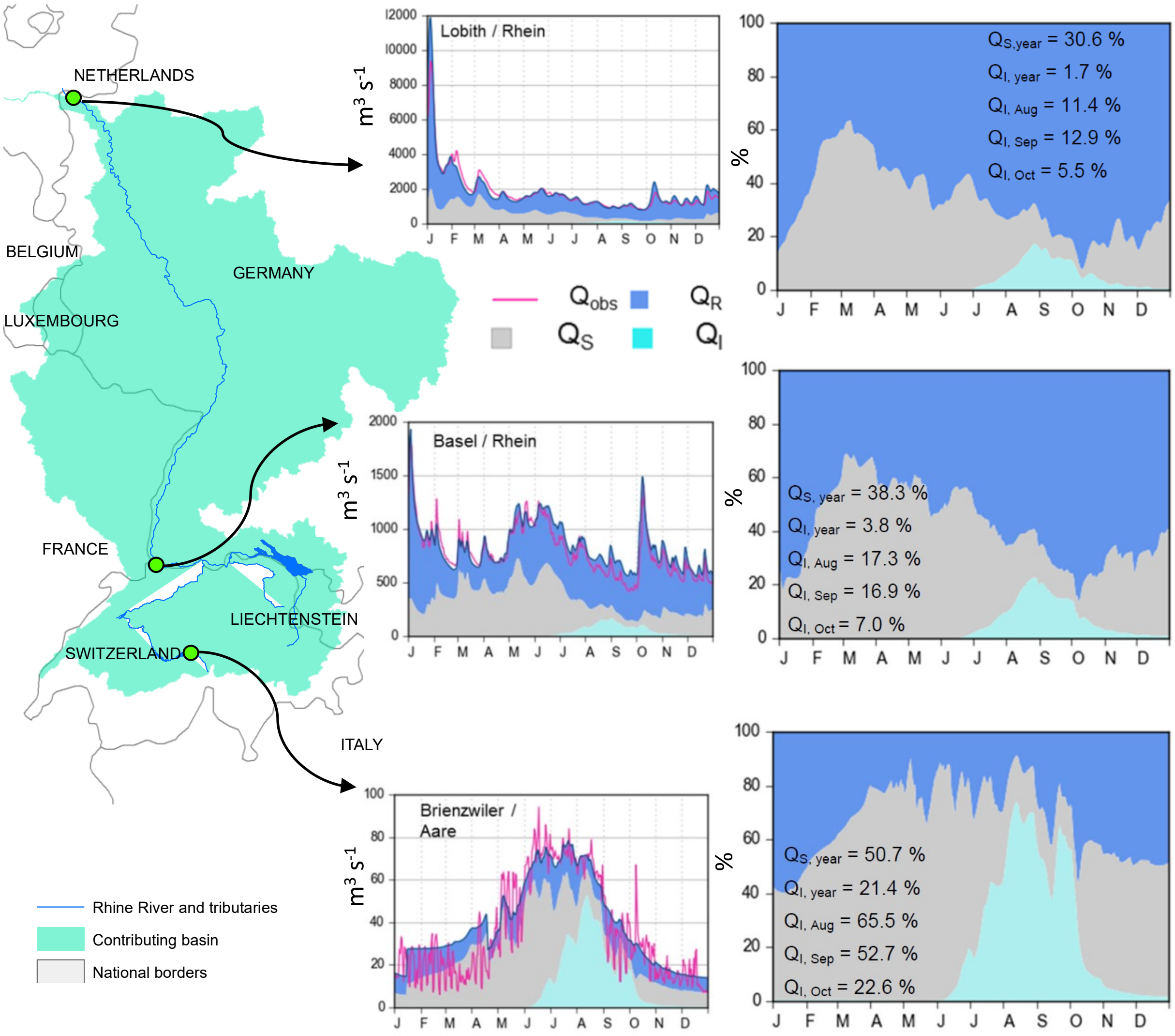

Figure 2.2: The role of ice melt along the Rhine River during drought conditions according to the CHR project. Absolute and relative estimated contributions of rain, snowmelt and ice melt to runoff are presented at the locations of Brienzwiler, Basel and Lobith in year 2003. Q_{obs}: Observed discharge, Q_R: Rain component, Q_S: Snow component, Q_I: Ice component. Adapted from Stahl et al. (2017).

decreased between 63±11% (RCP2.6) and 94±4% (RCP8.5) compared to 2017 values (Figure 2.3). For Switzerland, which presently hosts about ~60% of the total glacier volume of the European Alps, the figures are very similar: ~59% and ~93% of the present-day glacier volume is anticipated to be lost by 2100 for RCP2.6 and 8.5, respectively (Zekollari et al., 2019). The results of the study have now been used in specific works addressing, for example, the potential of alleviating water scarcity in Switzerland through reservoirs and lakes (Brunner et al., 2019a) or the projected shifts in extreme flow regimes in the Swiss Alps (Brunner et al., 2019b). Similarly, the results are included in the new hydrological scenarios for Switzerland that are in development (Mülchi et al., 2019).

For Switzerland, the findings of Zekollari et al. (2019) are slightly less negative than the ones provided by earlier projections. For the year 2100, for example, the study projects a total ice volume loss of ~59% under a RCP2.6 scenario, whilst Huss and Hock (2015) estimated a ~76% loss. For RCP8.5, these figures change to ~93% (Zekollari et al., 2019) vs 98% (Huss and Hock, 2015). The differences are to be sought in the higher-resolution climate data used

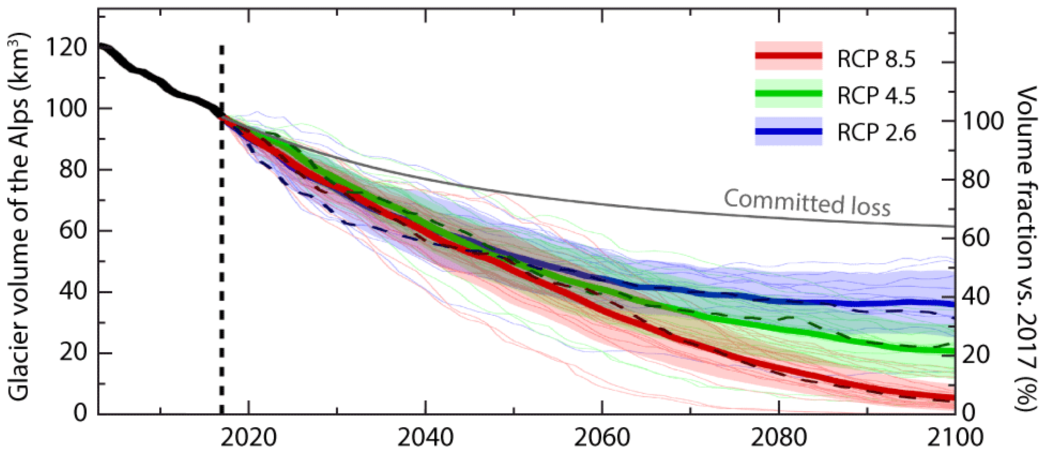

Figure 2.3: Evolution of the total ice volume for all glaciers in the European Alps (adapted from Zekollari et al., 2019). The simulations are driven by the EURO-CORDEX climate model ensemble, which is at the base of the CH2018 scenarios. Results for individual model chains (thin lines), the ensemble mean (thick lines) and an empirical 1σ confidence interval (semi-transparent bands) are shown for thee RCPs (colours). "Committed loss" (grey line) indicates the ice volume evolution that would result if climate was stabilized at the 1988-2017 level from 2017 onwards. The ice volume remaining by 2100 under RCP2.6, RCP4.5 and RCP8.5 scenarios is of 36.8%, 21.2% and 5.6%, respectively (values refer to the ensemble mean and a 2017 baseline). Results for Swiss glaciers obtained with the Global Glacier Evolution Model (Huss and Hock, 2015) are shown in Figure 2.1.

by the more recent study (EURO-CORDEX regional climate models, as opposed to global climate model outputs), the different approach to compute the glacier evolution (explicit ice flow modelling vs. parametric approach), as well as the updated glacier ice thickness information (Farinotti et al., 2019a) and calibration data (e.g. Zemp et al. ,2019) that have become available after 2015.

A more focused, glacier-related study directly based on CH2018 scenarios, was presented by Jouvet and Huss (2019). This study addresses the future evolution of Grosser Aletschgletscher using a higher-order ice flow model until the year 2100. In line with the regional scale picture, the glacier is projected to lose between ~57% (RCP2.6) and ~97% (RCP8.5) of its 2017 ice volume – a grim perspective for the largest glacier in the European Alps.

Another, broader ongoing initiative with some relevance for glacier changes is that of the Swiss Competence Centre for Energy Research, Supply of Electricity (SCCER-SoE). Funded by the Swiss National Science Foundation (SNSF) and the Commission for Technology and Innovation (CTI), SCCER-SoE is a consortium of 30 Swiss scientific institutions, companies and national agencies that aim at fostering the use of geo-energy and hydropower to secure the Swiss electricity supply. An important activity ongoing within SCCER-SoE and with relevance to glacio-hydrological research is the measuring of the total ice volume in the Swiss Alps (Grab et al., 2017; Langhammer et al., 2019). As the current volume stored in a glacier determines its long-term evolution and runoff generation (Gabbi et al., 2012), results from this project will be of high value for regional simulations. Other relevant projects within SCCER-SoE are those related to decadal hydro-glaciological forecasts for the Swiss hydropower sector (Gindraux et al., 2017, 2018) and the sediment supply from periglacial and subglacial environments (Delaney et al., 2017, 2018; Ehrbar et al., 2017).

Take-home messages

All reviewed studies carried out in the period 2008-2015 project significant reductions in ice volumes stored in Swiss glaciers by 2100. Results from a regional glacier model accounting for ice flow dynamics (Zekollari et al., 2019) project that, by the end of the century and compared to 2017, the total ice volume of all Swiss glaciers will decrease by 59%, 75%, and 94% under low (RCP2.6), moderate (RCP4.5) and severe (RCP8.5) emission scenarios, respectively. These figures are slightly less negative than earlier studies (e.g. Huss and Hock, 2015) but consistent with individual, glacier-specific studies (e.g. Jouvet and Huss, 2019).

Despite the large ice volume loss, little change is projected for the total amount of water available at the national level. The hydrological regimes of glacierized catchments, however, will gradually be transformed into regimes that are more typical for lower altitudes.

Reviewed works typically report uncertainties between 20 and 30%, the main uncertainties being related to the unknown future climate evolution, to poorly constrained glacier ice volumes at the present stage, and to the effects of some poorly understood processes. Results from ongoing initiatives, such as CH2018 and SCCER-SoE, will help to reduce such uncertainties, particularly those related to transient time series, inter-annual and diurnal variability, extreme events, and estimates of current ice volumes.

3. Recent advances in understanding and predicting future glacier evolution

The future evolution of Swiss glaciers has been addressed in a series of glaciological, hydrological and climate change investigations. Substantially influenced by the activities described in the last section, the number of peer-reviewed articles has significantly increased during the period 2008-2014 (Figure 3.1). This progress, however, has also been facilitated by the high quality and availability of glacio-hydrological observations in Switzerland. In this section, recent advances in climate change impacts studies on Swiss glaciers and their water resources are reviewed, and some of the possible paths for future research are outlined.

After some pioneer attempts to simulate glacier evolution under climate change scenarios (Haeberli and Hoelzle, 1995; Oerlemans et al., 1998), the number of studies about climate change impacts on Alpine glaciers greatly increased during the last decades. In this period, several studies were conducted, focusing on glacier evolution (Zemp et al., 2006; Huss et al., 2007; Paul et al., 2007; Sugiyama et al., 2007; Jouvet et al., 2009, 2011, 2019; Huss, 2012; Linsbauer et al., 2013; Zekollari et al., 2014, 2019) or glacier contribution to runoff (Huss et al., 2008, 2010, 2014; Huss, 2011; Huss and Fischer, 2016; Farinotti et al., 2012, 2016; Salzmann et al., 2012; Finger et al., 2012; Uhlmann et al., 2013a, 2013b, Fatichi et al., 2014, 2015; Pellicciotti et al., 2014; Terrier et al., 2015; Rahman et al., 2015). The models and tools developed in these studies, and the increase of computational capacities, have fostered the understanding of long-term evolution of Alpine glaciers.

There is strong consensus about the large impacts that an increase in air temperature would produce on Swiss glaciers and associated water resources. In fact, it has been shown that the response of glacierized catchments can be better projected than that of low-elevation catchments (Addor et al., 2014). This is because changes in future air temperatures (that control glacier evolution) can be better predicted than changes in precipitation (that control runoff in non-glacierized basins), which are enveloped by natural variability (Fatichi et al., 2014). However, the scientific literature is also consistent in acknowledging the uncertainties that affect such projections.

After 2014, much of the academic focus has moved to other regions in the world, particularly also the Poles and the Himalayas. Recent glacier simulations of the Swiss Alps have either been conducted within global models – such as the studies by Bliss et al. (2014) and Huss and Hock (2015, 2018) – or have addressed specific questions, such as the future evolution of very small glaciers (Huss and Fischer, 2016) or the mitigation potential of new artificial lakes in presently glacierized areas (Farinotti et al., 2016, 2019b). Recently developed global glacier models project volume changes between -84 ± 10% (Radic et al., 2014) and -89 ± 8% (Huss and Hock, 2015) for Central Europe under the RCP4.5 scenario. Under the severe RCP8.5 scenario, European glaciers are expected to almost completely disappear.

A concept that has gained popularity when communicating possible scenarios of future glacier evolution, is the “committed ice loss” that would occur if climate was stabilized at present-day conditions (Marzeion et al., 2018). Zekollari et al. (2019) quantified such a committed ice loss for the whole European Alps. Their results indicate that by 2100, stabilizing the climate at the average 1988-2017 conditions would result in a total ice loss of ~40km^3 – or ~37% of the ice volume present in 2017 (Figure 2.3). Such results do not only visualize the delayed response that glaciers have with respect to climate (Zekollari et al. in review) but also powerfully demonstrate that important future changes are to be expected in all cases.

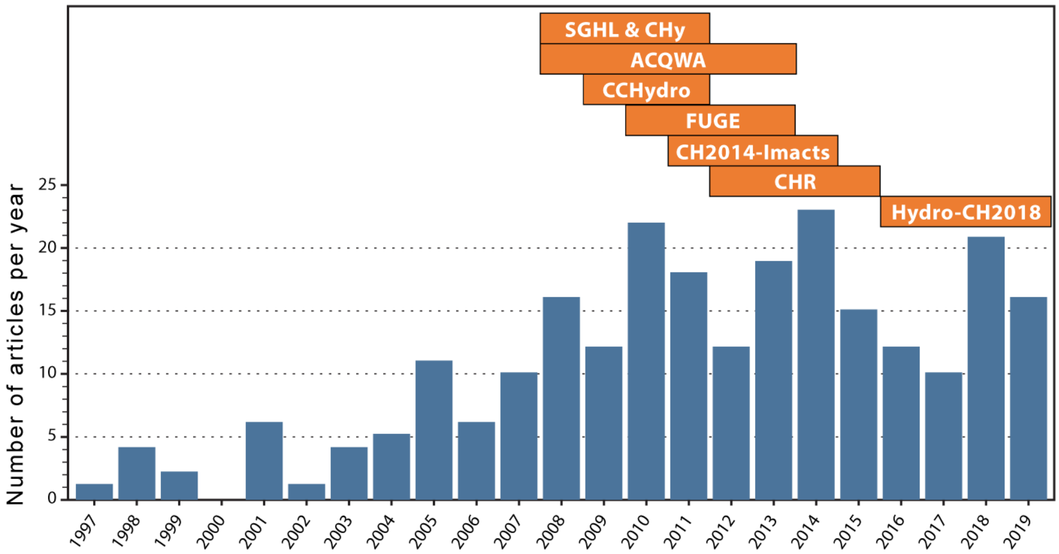

Figure 3.1: Annual number of publications (blue) in the Science Citation Index containing the terms "glacier", "Switzerland" and "climate change" between 1997 and 2019. The period in which the reviewed projects took place is shown in orange. Data were extracted from https://apps.webofknowledge.com.

3.1 Modelling studies and process understanding

Huss and Fischer (2016) performed simulations of future mass balance and runoff generation from "very small glaciers" (i.e. glaciers with an area smaller than 0.5 km^2). Very small glaciers are frequently neglected in glacier models, but account for more than 80% of the total number of glaciers in low to mid latitudes. They thus contribute significantly to both landscape formation and local hydrology. The study found that in Switzerland, 52% of these small glaciers will disappear within the next 25 years (Figure 3.2). Despite the projected increase of air temperature, a few avalanche-fed glaciers at low-elevation are likely to survive significantly longer. The authors highlighted that the mass balance sensitivity of these glaciers to changes in air temperature varies across study sites depending on the slope, elevation, and the presence of supraglacial debris.

Farinotti et al. (2016) addressed the question whether reservoirs located on new proglacial areas could theoretically replace glaciers in their function as storage of water resources. As addressed in several studies (Frey et al., 2010; FOEN, 2012; NELAK, 2013; Haeberli et al., 2016, 2017; Magnin et al., 2020), glacier retreat will expose areas of overdeepened bedrock in which new lakes may form. Apart from the increased risk of local natural hazards (Haeberli et al., 2017), this might offer opportunities for hydropower (Haeberli et al., 2016; Ehrbar et al., 2018; Farinotti et al., 2019b). The idea behind the investigation by Farinotti et al. (2016) was to transfer the water that, in future, will become additionally available in spring (due to earlier snow and ice melt, as well as changes in the rainfall-to-snowfall ratio) to late-summer, thus mitigating the water deficit caused by future ice loss (Figure 3.3a). The study estimated that by 2100, such a strategy could offset up to 65% of the expected summer runoff changes, and that the potentially installable storage volume in deglacierized catchments is one order of magnitude larger than the required one. Although the results suggest that less than a dozen reservoirs would be sufficient for providing the necessary total volume (Figure 3.3b), the authors warn that such a solution cannot compensate for the net reduction in annual water

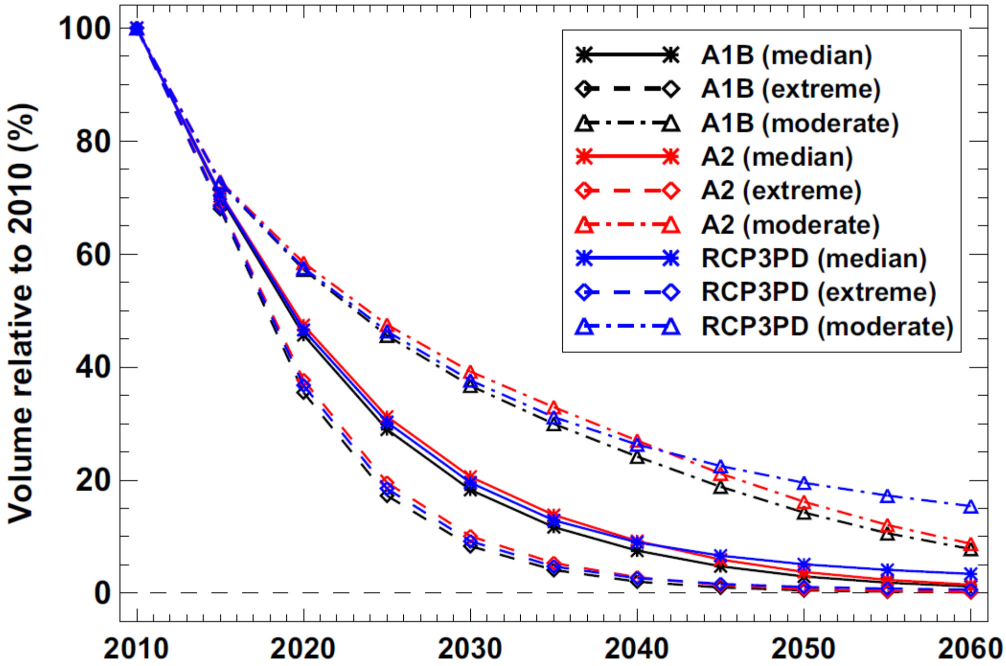

Figure 3.2: Future projections for the ice volume of "very small glaciers" (<0.05 km^2) in Switzerland (from Huss and Fischer, 2016). The results are relative to 2010 and are shown for three CO2-emission pathways (A1B, A2, RCP3PD). For each pathway, a median, an extreme, and a moderate scenario is given. By 2060, more than 80% of the current volume is expected to have melted. The A1B scenario represents a globalized world with rapid economic growth and a balanced emphasis on all energy sources (similar to RCP 6.0); the A2 scenario represents an independent-nations world with regionally oriented development (similar to but less extreme than RCP 8.5); the RCP3PD scenario is similar to RCP2.6.

yields. Variations of ice albedo are a further key for the future mass balance of Swiss glaciers, and some studies have specifically addressed the topic. Gabbi et al. (2015), for example, analysed the effect of black carbon (BC) and Saharan dust deposition on Claridenfirn Glacier. The study took advantage of a remarkably long time series of mass balance, and compared those data to dust deposition estimates obtained from two ice cores drilled in high-alpine glaciers. The presence of Saharan dust and BC significantly lowered the mean annual albedo and increased annual melt by 15-19%. These results suggest that regional circulation patterns and their transport of dust and impurities from other regions may be of great importance for Alpine glaciers. Thus, the modelling of such processes in atmospheric simulations can be crucial for glacier ablation.

It is well known that the thermal insulation effect of supraglacial debris can largely affect local ablation (Brock et al., 2010; Reid and Brock, 2010). Although most of the recent works have been targeting the Himalayas, it has to be noted that debris-covered areas may be of relevance in the Swiss Alps as well (Jouvet et al., 2011; Pellicciotti et al., 2014), especially for glaciers such as Oberaletsch and Unteraar. Glacier models, such as TOPKAPI-ETH and GERM, have included parameterizations for the thermal insulation effect of debris, but these parameterizations are usually applied to static debris-cover areas. The dynamics of supraglacial debris are still poorly understood and therefore not usually included in glacier models. A notable exception is the work by Rowan et al. (2015) who developed the first numerical model explicitly accounting for debris transport within glacier ice. The authors

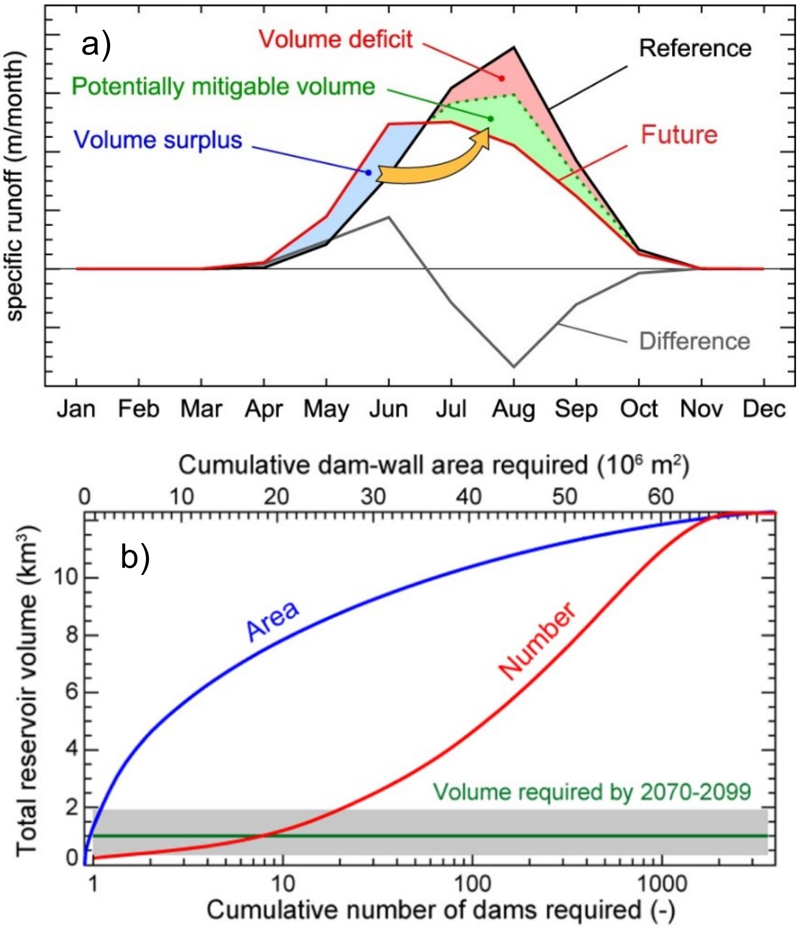

Figure 3.3: Exploring the installation of reservoirs on new proglacial areas formed by glacier retreat. (a) Conceptual illustration of the potential mitigation through water management. Volume surplus (light blue) is the runoff volume that, according to the projection, will be in excess to the runoff in the reference period during late spring and early summer. This volume could potentially be transferred into late summer and early autumn (arrow) in order to partially compensate (light green) the runoff reduction caused by glacier depletion. Volume deficit (light red) is the net reduction in annual runoff. (b) Comparison of required and hypothetically available storage volume. Cumulative number of dams (red) and wall-dam area (blue) required for achieving a given total storage volume according to the virtual set of constructed reservoirs. The storage volume required for achieving the maximal potential mitigation at the end of the century (2070-2099) is shown (green). The grey band represents the uncertainty due to GCM spread, considered RCP, and year-to-year variability. Adapted from Farinotti et al. (2016).

demonstrated that including this process prolongs the response of the glacier to warming, and causes the glacier surfaces to lower without major changes in glacier area. Other small-scale surface features, such as ice cliffs and supraglacial ponds, have long been described in the glaciological literature (Sakai et al., 1998, 2000; Nakawo et al., 1999; Adhikary et al., 2000; Mihalcea et al., 2006, 2008; Brock et al., 2010), but advances in their mapping and description (e.g. Immerzeel et al., 2014; Brun et al., 2016; Thompson et al., 2016; Vincent et al., 2016; Kraaijenbrink et al., 2018), as well as their modelling (e.g. Buri et al., 2015, 2016; Steiner et al., 2015; Wirbel et al., 2018) have been achieved only recently.

3.2 New remote sensing products and technologies

Complementary to modelling contributions, the constant development of remote sensing products and the appearance of new monitoring techniques will be relevant for the validation and further development of glacier evolution and water discharge models, ultimately helping to produce more reliable projections. Here, some of the most important advances during recent years are discussed, such as remote sensing programmes, new on-site high-resolution monitoring techniques, and the use of seismic sensors.

Over the last decade, satellite products have been one of the most relevant tools in geosciences in general, and in glaciology in particular. Established satellite missions and sensors such as Landsat, SRTM, ASTER, and MODIS, have provided a robust base for deriving DEMs, glacier inventories, and snow-covered areas. One the most remarkable advances has been the development of global glacier products, such as the RGI. New programmes using additional and improved technical features now produce more frequent monitoring, and with higher resolution than classic products. In this direction, ongoing public and private programmes, such as TanDEM-X, Pleaides, Cryosat, Sentinel and Planet, retrieve information using several optical, radar, and microwave sensors. An extensive review of these products is beyond the scope of this report, and only some of the recent glaciological applications are highlighted hereafter. For a more detailed review on the subject, the reader is referred to Tedesco (2015).

Among the latest developments, the Sentinel programme of the European Space Agency (ESA) is one of the most promising. Optical products from mission 2 (Sentinel-2) offer an improved resolution compared to the widely-used Landsat products (Figure 3.4), and have already been used, for example, to monitor glacier-related hazards (Tian et al., 2017), or surging glaciers (Round et al., 2017; Steiner et al., 2017). In the Swiss Alps, Naegeli et al. (2017) showed the ability of narrow-to-broadband conversion algorithms applied to Sentinel-2 images to estimate ice albedo, which can be useful for large-scale glacier mass balance applications. Remote sensing products using interferometric synthetic-aperture radar (InSAR) techniques, such as the ones obtained from the Sentinel-1 suite, offer additional examples of glaciological applications, particularly in the retrieval of surface ice flow velocities (Rankl et al., 2014; Vijay and Braun, 2016, 2017). Also new processing techniques have contributed to add value to the acquired satellite products. Analysing ASTER stereo imagery, for example, Berthier et al. (2016) paved the way for spatially-resolved, large-scale geodetic mass balance calculations. Such methods have now been exemplarily applied for glaciers in High Mountain Asia (Brun et al., 2017) and other parts of the world (e.g. Berthier and Brun, 2019; Dussaillant et al., 2019; Menounos et al., 2019).

Repeated high-resolution DEMs can precisely monitor glacier surface changes at unprecedented timescales, including sub-daily and seasonal scales. The derived DEMs allow for the identification of small-scale features and processes that have been neglected or over-simplified in glacier models. Such processes and features include snow deposition and redistribution, crevasses, moulins, ice cliffs and supraglacial ponds, among others. High-resolution monitoring of glacier surfaces first appeared in glaciological studies about 10 years ago, and was mostly conducted using terrestrial or aerial Light Detection And Ranging (LiDAR) techniques (Arnold et al., 2006). LiDAR techniques have been used to map snow accumulation over glacier surfaces (Sold et al., 2013; Helfricht et al., 2014), derive sub-daily ablation rates (Gabbud et al., 2015) and identify microtopographic controls of the glacier surface energy (Arnold et al., 2006) and mass balance (Fischer et al., 2016). The relatively high costs of the instruments have, however, limited the widespread extension of such techniques. Close-range photogrammetry based on Unmanned Aerial Vehicles (UAVs) offers an alternative to LiDAR, significantly lowering the cost of obtaining repeated DEMs

(Immerzeel et al., 2014; Gindraux et al., 2017). Notably, UAV-based photogrammetric DEMs have been shown to potentially achieve the same level of accuracy as LiDAR-derived DEMs (Hugenholtz et al., 2013; Whitehead et al., 2013). Unfortunately, logistic and technical limitations still affect the use of UAVs in harsh, high-elevation environments, such as glacier accumulation areas. Low-lying glacier tongues, however, have been shown to be relatively easy environments to monitor (Immerzeel et al., 2014; Bhardwaj et al., 2016).

Finally, one of the most rapidly growing branches in glaciology, with a potential to contribute to the understanding of meltwater discharge, is cryoseismology. In cryoseismological studies, seismic signals from a variety of sources are interpreted to gain insights into glacier-related processes (Podolskiy and Walter, 2016). Seismic sensors provide new information at very high temporal resolution about englacial and subglacial water discharge processes that determine the drainage of large areas. Gimbert et al. (2016) showed, for example, the value of seismic observations to monitor changes of water pressure gradients, channel size and sediment transport in Mendenhall Glacier (Alaska). Additionally, it has been suggested that cryoseismology can provide new data for constraining ice flow parameters (Kyrke-Smith et al., 2017). A number of studies based on such approaches are now available in the Alps (Walter et al., 2008, 2013), mostly targeting at the ice body structure and motion. A detailed discussion on the use seismic sensors in glaciology is found in the reviews by Podolskiy and Walter (2016) and Aster and Winberry (2017).

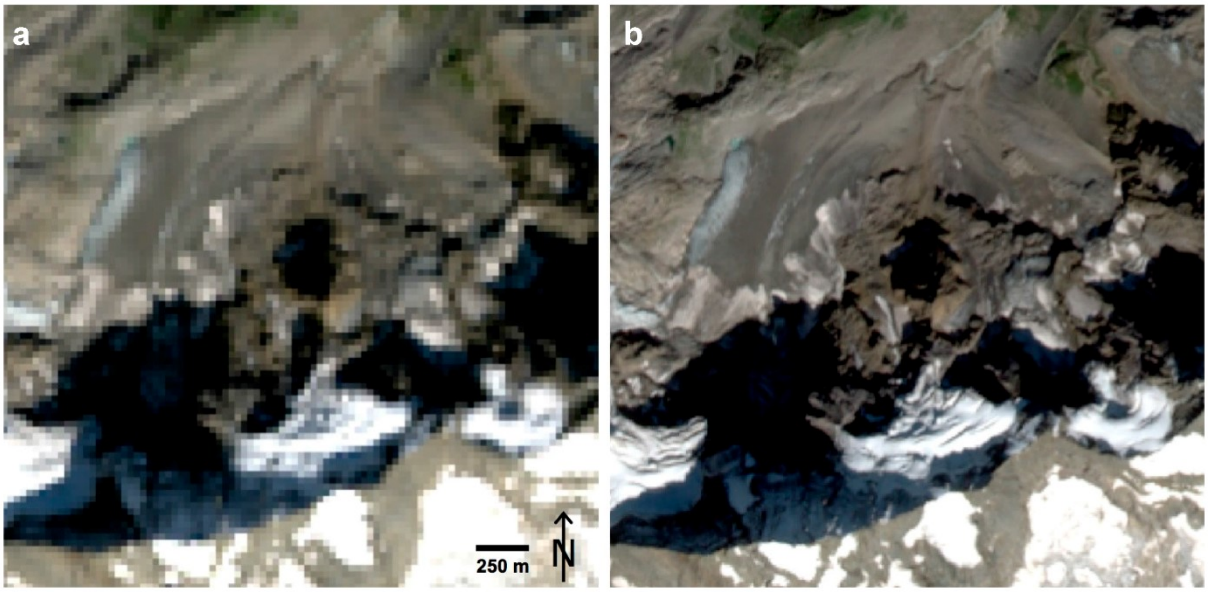

Figure 3.4: An example of the progress achieved by new satellite products, and the great potential for delimiting glacier outlines, identifying surface features, and mapping glacier retreat. The image shows a comparison between the Landsat 8 (a, OLI bands at 30 m resolution) and Sentinel 2 (b, MSI bands at 10 m resolution) missions. The image width is 2.8 km and refers to the Breithorngletscher in the Lauterbrunnental, Canton Bern, Switzerland. From Paul et al. (2016).

3.3 A case study for Findelengletscher

Findelengletscher – a temperate glacier located in Canton Valais, close to Zermatt (Figure 3.5) – is an interesting example for elucidating the topics discussed so far. The glacier has been the target of a large number of glacio-hydrological studies in the recent past. According to the SGI2010, the glacier had an area of 13 km^2 and a length of 6.7 km in 2010.

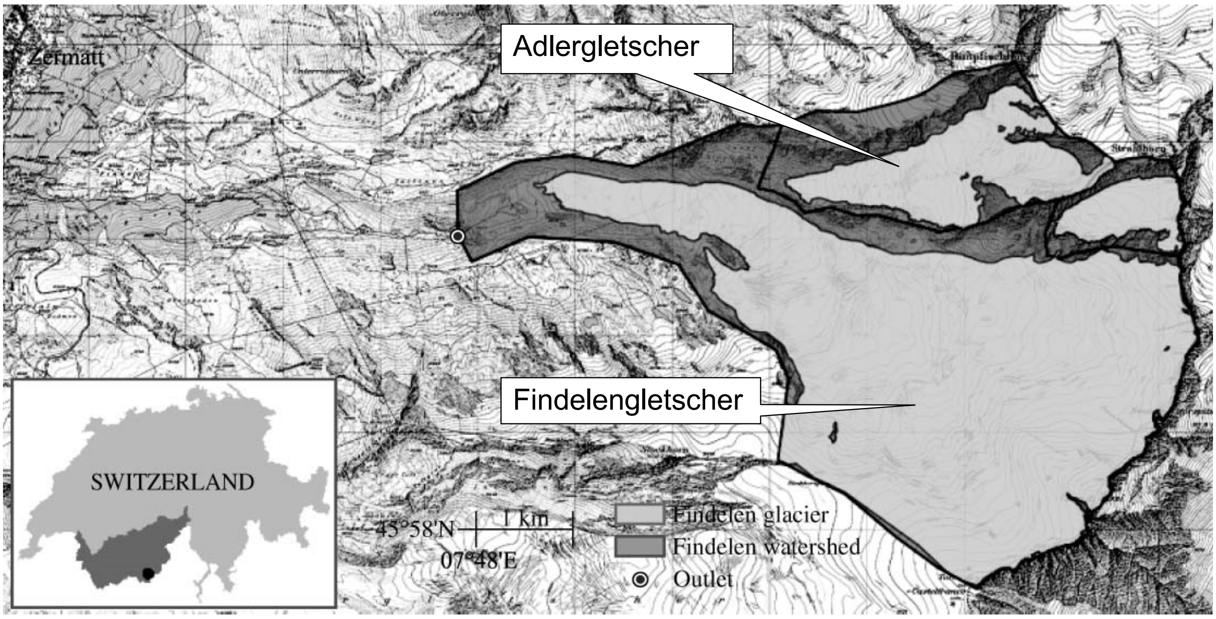

Figure 3.5: Findelengletscher and the watershed defined by the closest gauging station. The watershed also contains Adlergletscher. From Uhlmann et al. (2013).

Since 1850, the glacier is estimated to have lost about 3.5 km of length, 4.4 km^2 of area, and 1.32 km^3 of volume. The historical retreat of Findelengletscher since 1850 has been recently depicted by Rastner et al. (2016). Projections of future glacier evolution and water discharge were calculated using GERM in the report by VAW (2011), which was part of the CCHydro project. According to that report, the ice volume is anticipated to decrease by 85% (from 2.10 to 0.32 km^3) under the A1B scenario during the period 2010-2090. Meltwater discharge has increased in about 20% since 1980, and is anticipated to undergo only small changes until 2060. After that, the ice melt runoff contribution will start decreasing due to the reduced ice volume. In another study, Uhlmann et al. (2013a; 2013b) used a conceptual hydrological model (Routing System 3.0) to simulate the contribution of snow- and ice-melt and their relation to infiltration and runoff processes. The authors estimated that the glacier would remain out of balance for at least 40 years even if current climatic conditions were to remain constant. They also found that the shift in the seasonal runoff from late summer to spring is evident in all simulations. While a rapid glacier wastage is expected to occur with high probability, uncertainties associated with these calculations are large. Huss et al. (2014) used the Findelengletscher catchment to illustrate how uncertainties in the forcing data and glacier model parameters are propagated to runoff projections. Initial ice thickness, amount and spatial distribution of snow accumulation, and glacier retreat model were found to have the largest effects on future runoff. Notably, it was estimated that future runoff in August can vary from -94% to -5% by the end of the 21st century due to uncertainties in model input data and model parameterizations.

In recent years, Findelengletscher has been one of the preferred testbeds for the application of new monitoring techniques and satellite products (cf. Section 3.2). These studies have strongly benefited from a long record of length variations reaching back to 1885 and a detailed mass balance monitoring program starting on 2004 that has produced key datasets of snow accumulation and volumetric changes (Machguth, 2008, Sold et al., 2016). For example, Machguth et al., (2006) used helicopter-borne radar measurements on Findelen-and Adlergletscher to study and compare patterns of snow accumulation over Alpine glaciers. They found a strong spatial variability of snow accumulation with different total amounts and patterns over the upper and lower areas of both glaciers. More recently, Sold et al. (2013) and Sold et al. (2015) proposed new approaches for the modelling of snow accumulation based on a combination of Lidar, GPR and manual measurements. Additionally, methodological issues of geodetic mass balance techniques have been addressed using data from aerial Lidar surveys (Joerg and Zemp, 2014). In very recent studies, Naegeli et al. (2017, 2019) showed the value of new Sentinel-2 imagery to estimate broadband ice albedo and Gindraux et al. (2017) assessed the accuracy of DEMs generated from UAV imagery, finding accuracy values between 0.10 and 0.25 m.

Take-home messages

In recent years, models of future glacier evolution have been extended to regional- and global-scale applications. Glaciological research has mostly focused on regions other than the Alps, including the Himalayas, the Arctic, and the Antarctic. With a few exceptions, recent studies in the Swiss Alps focus on specific issues, such as improved process understanding, snow accumulation distribution, proglacial lakes, or albedo changes.

New generations of satellite products will continue opening paths for glacio-hydrological studies. Information from remote regions and areas with difficult access can be expected to improve significantly. New monitoring techniques, such as UAVs and seismic sensors, will additionally provide novel datasets and further insights in as-yet-poorly-constrained glaciological processes.

The series of studies conducted on Findelengletscher offer an interesting example of the recent evolution in glaciological research and highlight the importance of glacier monitoring programs.

4. Implications of projected glacier changes on Swiss water resources

4.1 Water availability

In the long term, ongoing glacier retreat will decrease the specific runoff of currently glacierized areas. This will result in reduced annual and summer discharge from Alpine headwaters (Huss et al., 2008; Farinotti et al., 2012; Salzmann et al., 2012; Uhlmann et al., 2013). The two main clusters of Alpine glaciers in Switzerland – at the Swiss-Italian-French and Swiss-Italian-Austrian borders – provide significant runoff contributions to the low-lying rivers in the region, particularly in summer (Figure 4.1a; Huss, 2011; Farinotti et al., 2016). Significant changes in these summer values are anticipated by the end of the 21st century (Figure 4.1b). As pointed out in the final results of ACQWA (2013), CCHydro (FOEN, 2012) and CH2014-Impacts (2014), however, it has to be noted that at the annual scale and for large-scale basins, runoff volumes are likely to remain constant or to experience little change. This is mainly a result of a shift in runoff from summer to winter, and a relatively small change in future precipitation amounts. The large natural variability of precipitation additionally masks the projected precipitation changes, particularly in low-elevation basins (Fatichi et al., 2014).

The reduction of ice volume stored in Alpine glaciers implies that runoff generation in high-elevation sites will be more dependent on seasonal precipitation. High-elevation catchments, thus, will be more exposed to inter-annual variability in precipitation, and will be more vulnerable to droughts (Beniston, 2012; Finger et al., 2012). In relation to seasonal changes, there is large consensus that the anticipated raise in air temperature will impact hydrological regimes by shifting the seasonal runoff peaks from late summer to spring (Finger et al., 2012; Addor et al., 2014; Köplin et al., 2014).

As the runoff contribution of glaciers is most critical for water supply during low-flow periods in summer (droughts), these events have been studied in more detail during recent years. Alpine glaciers notably mitigated the drought of the summer 2003, and their effects were significant as far as Lobith (The Netherlands), more than 800 km downstream of the Rhine headwaters (Huss, 2011; Stahl et al., 2017). The mitigating effect of glaciers during droughts has recently been shown in other regions of the world such as the Himalayas (Huss and Hock, 2018) and the Andes (Ayala et al., 2016). As drought episodes in the Swiss Alps are likely to become more frequent (Beniston, 2012; Gobiet et al., 2014), accurate projections of the ice melt runoff-share along Swiss and European streams (Stahl et al., 2017) can provide relevant information for water management.

Examining both extreme low- and high-flow regimes until the end of the 21st century, Brunner et al. (2019b) recently highlighted how changes that are expected for melt-dominated areas differ from those anticipated in rainfall-dominated regions. For melt-dominated areas, the minimum discharges of extreme regimes were found to increase by up to 100%, whilst the maximum discharges of such regimes were projected to decrease by 50% or less. In rainfall-dominated regions, instead, the changes pointed in the opposite direction: the minimum discharges of extreme flow regimes were projected to decreases by 25 to 50%, whilst the maximum discharges of such regimes were found to increases by up to 50%.

Brunner et al. (2019a) analysed the potential for artificial reservoirs and natural lakes to the bridge periods of water scarcity that could emerge from such regime changes. The study quantified the water demand for drinking water, industrial use, artificial snow production, agriculture, ecological flow requirements and hydropower production, and compared that to the storage capacity of reservoirs and natural lakes for 307 basins across Switzerland. The results showed that water shortages are mainly expected to occur in the lowland regions north of the Alps, and that the potential for natural lakes to alleviate water scarcity in such regions is high. Water scarcity was estimated to be less problematic in the Alps, but the study also indicated the smaller potential for alleviating future water shortages at higher elevations.

4.2 Hydropower production

For what the link between glacier runoff and hydropower production is concerned, Schaefli (2015) identified the forecasting of "peak water" (that is the point in time at which the total runoff, and thus hydropower production, is maximal for a given catchment) as the largest open question. As discussed earlier, the timing of peak water is still uncertain and strongly varies depending on catchment properties (Farinotti et al., 2012; Salzmann et al., 2012). A recent study by Huss and Hock (2018) analysed this issue on a global scale. They found that the European Alps are expected to reach peak water in the first half of the 21st century. Schaefli (2015) also acknowledges that local impacts caused by proglacial lakes and sediment delivery can be far more relevant than the water availability issue. A new study by Schaefli et al. (2019) has shown that since 1980, 3-4% of the national hydropower production was directly linked to net glacier mass loss and this share will reduce significantly in upcoming decades (about 1 TWh yr^{-1} in the period 2070-2090). Future production losses have also been projected by comparable studies in the Italian Alps, where the median production is anticipated to decrease by ~3% until 2035 (Patro et al., 2018). The study mentioned glacier retreat as the major driver for the reduction.

The future of hydropower production in Switzerland is one of the main challenges addressed by the SCCER-SoE competence centre, and several publications have emerged by now (Manso et al, 2016a, 2016b; Matos et al, 2017). Again, the possible impacts of the anticipated long-term decrease in water availability due to glacier retreat gathers significant attention. In this context, however, additional uncertainties related to the evolution of future electricity markets affect the projections, and these uncertainties are usually even larger than those associated to climate change projections (SGHL and CHy, 2011; Gaudard et al., 2014). Driven by the current national energy strategy, and thanks to an increase in production efficiency and new infrastructure, it is likely that an increase in hydropower production will be achieved despite of the reduction in glacier runoff contributions (Manso et al., 2016a; Manso et al., 2016b; Ehrbar et al., 2018).

The announced phase out of nuclear power plants has added much pressure on hydropower plants, and Alpine reservoirs might play a key role in securing future energy demands. A recent study within SCCER-SoE (Guittet et al., 2016) suggested that an increase in the capacity to capture excess natural inflows (by means of dam heightening, the construction of new dams, or off-stream storage and reservoir interconnection) would be the strategy that most efficiently uses the remaining hydropower potential of Switzerland (as opposed to increasing inflows through pumping or gravity diversion from other basins, for example). Other studies suggest that the shift in runoff towards the winter, which is the season typically showing the highest energy consumption, could also contribute to increased hydropower production in glacierized catchments (Wagner et al., 2017). Finally, an analysis that explored the potential for new hydropower infrastructure in the periglacial environment (Ehrbar et al., 2018) indicates that for reaching the 1.1 TWh of additional hydropower production envisioned by the Swiss Energy Act until 2035, at least seven new hydropower plants would be required. To first order, these results are consistent with a more recent study that analysed such a potential at the global scale (Farinotti et al., 2019b).

4.3 Hazards related to glacier hydrology

Glacier-related hazards that are connected to hydrology, such as GLOFs or dangerous damming of proglacial streamflows through mass movements, are believed to increase in the future due to the strong modification of the alpine environment (Haeberli and Beniston, 1998; Stoffel et al., 2014b; Huss et al., 2017). Slope destabilization, loss of glacier debutressing, and the exposure of previously ice-covered terrain could lead to enhanced mass mobilization that, in turn, can affect floods and landslides (Beniston et al., 2011; Stoffel and Huggel, 2012; Huss et al., 2017). Such process chains have been observed in GLOFs events in which mass movements impacted glacial lakes triggering dam breaches and subsequent outburst floods (Worni et al., 2014). Debris flows are another frequent hazard in the Alps (Bollschweiler and Stoffel, 2010; Schneuwly-Bollschweiler and Stoffel, 2012), although it has been suggested that the frequency of such events could decrease if summer precipitation becomes less frequent (Stoffel and Beniston, 2006; Stoffel et al., 2014a). It is important to note that recent events such as the Piz Cengalo rockfall strongly challenge the preparedness of Switzerland to deal with major hazards, potentially including glacier-related ones.

Another potentially dangerous element is represented by glacier-dammed and proglacial lakes (Haeberli et al., 2016, 2017, 2019). GLOFs events from glacier-dammed lakes are long known in Switzerland (e.g. Ancey et al., 2019). A well-studied example is the drainage of a supraglacial lake on the lower Grindelwald Glacier, which in 2008 released about 500’000 to 800’000 m^3 (Werder et al., 2014; Worni et al., 2014). Additionally, repeated drainage events from Gornersee and Lac des Faverges (Glacier de la Plaine Morte) have been analysed and used in the assessment of future hazards (Huss et al., 2007; Huss et al., 2013). On the other hand, proglacial lakes do not only offer an opportunity to manage glacier runoff, but can also produce sudden water release with potentially catastrophic consequences (Frey et al., 2010; Worni et al., 2014; Haeberli et al., 2016). In this context, early planning and hazard prevention measures, such as lake-level lowering and flood retention, will become necessary (Frey et al., 2010; NELAK, 2013; Haeberli et al., 2016).

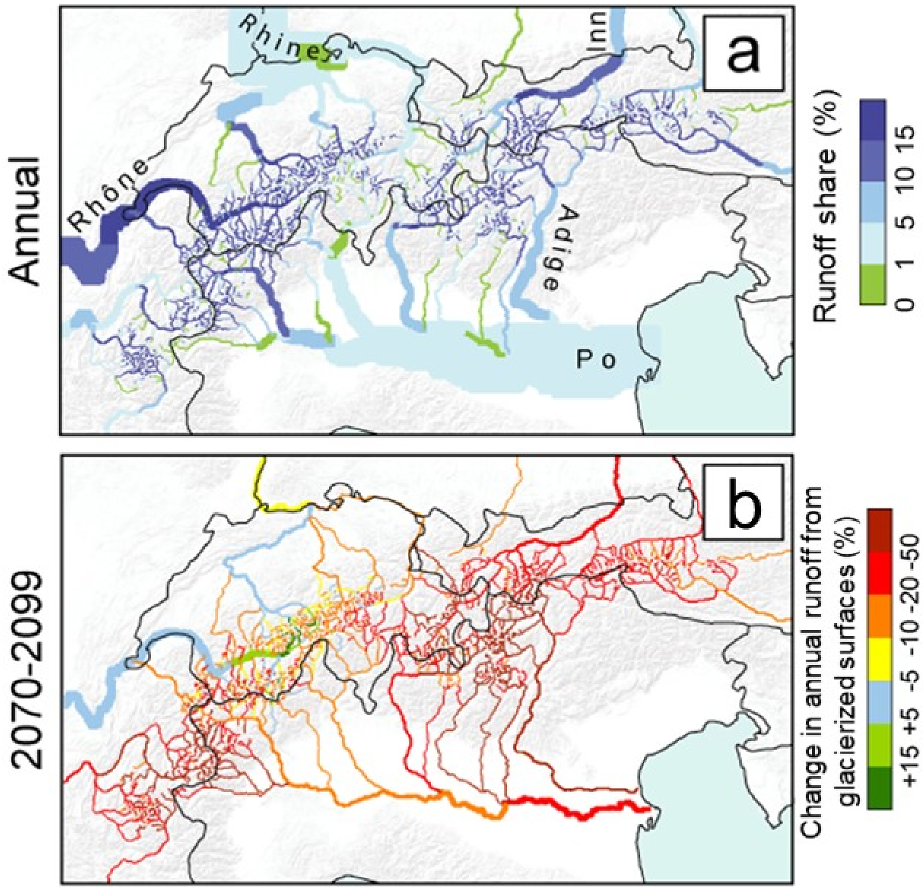

Figure 4.1: The anticipated effect of glacier retreat on the annual runoff of Alpine catchments (adapted from Farinotti et al., 2016). a) Mean annual runoff share from presently glacierized surfaces in the period 1980-2009. b) Expected change in the period 2070-2099. Changes refer to the RCP 4.5 scenario. River width is proportional to annual runoff (a) and the future runoff-share from glacierized surfaces (b).

Take-home messages

In the long-term, glacier retreat will reduce annual and summer discharges from Alpine headwaters, and glacierized catchments will shift their hydrological regimes from glacial into nivo-glacial and nival. Runoff generation in these catchments will be more dependent on seasonal precipitation, increasing their vulnerability to droughts.

The anticipated decrease of water availability and changes in runoff seasonality in glacierized catchments can affect hydropower production. Changes in electricity markets, however, are expected to be more important than those in water supply.

Glacier-related hazards connected to hydrological changes are expected to increase. Adequate strategies and planning are required to deal with them.

5. Research gaps and open questions

The retreat of Alpine glaciers will continue under the current climatic conditions (Mernild et al., 2013; Vaughan et al., 2013; Zekollari et al., 2019), but estimations of the timing and characteristics of glacier wastage and water discharge are affected by several uncertainties (Huss et al., 2014). The largest uncertainties originate from the spread between individual climate simulations for the 21st century (Farinotti et al., 2012; Gobiet et al., 2014; Kotlarski et al., 2015), the current ice volume stored in Swiss glaciers (Gabbi et al., 2012; Huss et al., 2014), the amount and distribution of winter snow (Helfricht et al., 2015; Sold et al., 2016; Freudiger et al., 2017), and the glacier retreat model (Paul et al., 2007; Huss et al., 2010). As mentioned in Section 2.2, the new set of climate projections prepared by CH2018 and the extensive helicopter-borne GPR measurements conducted within SCCER-SoE are expected to increase the reliability of simulated glacier changes.

In a review of the current challenges in cryospheric research, Hock et al. (2017) pointed out that accurate predictions of cryospheric variables are hampered by insufficient observations, process understanding, and modelling capacities. Insufficient observations of glacier variables is, in fact, a common issue in several regions of the world. In this respect, it is important to mention that Swiss glaciers are some of the best monitored glaciers in the world and long and detailed records of length and mass balance are available. At present, the Glacier Monitoring in Switzerland (GLAMOS) programme maintains and evaluates the long-term data series available for Swiss glaciers. The maintenance and extension of such a programme will be important for the long-term monitoring of global climate variability and the filling of some of the gaps in cryospheric science.

In relation to mountain glaciers, Hock et al. (2017) highlighted the modelling of basal processes and mountain meteorology as the main challenges. Progress on these topics will improve simulations of ice flow dynamics and snow accumulation, two key processes for future glacier evolution. In fact, the choice of the ice flow parameterization can significantly affect the results. Current ice flow parameterizations can be either physically-based and computationally expensive (e.g. Jouvet et al., 2009, 2011; Jouvet and Huss, 2019) or more empirical and inexpensive (Huss et al., 2010). In recent years, new studies have offered intermediate-complexity solutions that can be used for regional studies (Clarke et al., 2015; Zekollari et al., 2019). So far, however, these approaches are only rarely applied.

The spatial distribution of near-surface meteorological variables and their influence on melt has been the focus of extensive glaciological research in the past (van den Broeke, 1997; Oerlemans, 1998). As numerically resolving the glacier boundary layer is computationally expensive, researchers have traditionally opted for simpler strategies. The air temperature distribution, for example, has been based on lapse rates and some modifications driven by local phenomena, such as katabatic winds (Greuell and Böhm, 1998; Shea and Moore, 2010; Ayala et al., 2015). Importantly, estimates of snow accumulation on glaciers remains still very uncertain. Although snow accumulation can be now measured with high accuracy (e.g. Machguth et al., 2006; Gindraux et al., 2017), the high complexity of processes such as preferential deposition, orographic enhancement of precipitation, and wind and gravitational redistribution, complicates the development of appropriate strategies in glacio-hydrological models (Freudiger et al., 2017). Explicit numerical representation of the underlying meteorological equations (Sauter and Galos, 2016) or dynamical downscaling methods from GCMs (Mölg and Kaser, 2011; Collier et al., 2013) are possible avenues for future research.

The significance of other research gaps associated with poorly-understood glacial processes are sometimes debated and might be site-related. Huss et al. (2014) analyses on

Findelengletscher, for example, indicated that the uncertainties produced by the choice of a downscaling method, the calibration data quality, the melt model, and the thermal insulation of the debris cover are of secondary importance. At other study sites, it has been found that the debris-cover might substantially influence glacier mass balance (Collier et al., 2015; Pellicciotti et al., 2015; Vincent et al., 2016), and that the use of empirical melt models based only on air temperature may introduce biases in long-term simulations (Gabbi et al., 2014). Englacial and subglacial hydrological processes, and their connection to sediment transport, are also poorly understood processes that could play a role in future projections of glacier hydrology (Delaney et al., 2017; Lane et al., 2017). This is particularly true for debris-covered glaciers that exhibit supraglacial lakes and ice cliffs (Miles et al., 2016; Watson et al., 2017).

The modelling of landscape evolution in periglacial environments also requires further work. The actual formation of ice-dammed and moraine-dammed lakes, which depends on local geomorphological characteristics and processes (Carrivick and Tweed, 2013; Tweed and Carrivick, 2015), is for example not yet captured by numerical models. During recent years, potential sites for the formation of proglacial lakes have been mapped in the Alps (Haeberli et al., 2016), the Andes (Colonia et al., 2017) and the Himalaya (Linsbauer et al., 2016), but the results are in the need of verification. Results from the NELAK project (2013) suggest that between 500 and 600 new lakes could form in the Swiss Alps by the end of the century, with a few lakes at Aletsch, Gorner, Otemma, Corbassière and Gauli having more than $50x10^6m^3$ of volume. Anticipating their formation reliably, and correctly estimating their hazard potential should be a focus in future studies.

Glacier retreat will generate a cascade of impacts affecting the landscape, human activities and ecosystems (Huss et al., 2017; Beniston et al., 2018). This calls for interdisciplinary projects integrating glacio-hydrological results with knowledge from other natural and social sciences. Such results will be important for developing strategies for the management of water from glacierized catchments (Bréthaut and Clarvis, 2014; Reynard et al., 2014).

Take-home messages

Several processes affecting future projections of Alpine glacier water availability are not well understood and are not adequately included in current glacier models.

Among these processes are the long-term evolution of ice albedo, the evolution of debris-covered glaciers, englacial and subglacial hydrological processes, processes at the glacier base, small-scale meteorology, sediment transport, and the morphological evolution of periglacial landforms.

There is also a strong need for interdisciplinary studies that integrate knowledge from natural and social sciences. Such projects will be key for a full understanding of the impact that glaciers retreat will cause on Alpine water systems.

6. Translating research findings into policy-relevant messages

The large rates of glacier retreat observed during the last decades have raised concerns about future water availability in mountain regions around the world, including the Swiss Alps. In Switzerland, the close cooperation between public offices, academia, and the industry has played a key role in generating knowledge about glacier change and its consequences for hydrology. The efforts preceding the CH2014-Impacts report generated a large body of research around these topics. With this report, advances achieved in the field after 2014 have been reviewed and placed in the context of previous work. The main findings can be summarized as follows:

- The most recent estimates based on numerical simulations accounting for glacier ice dynamics (Zekollari et al., 2019) estimate an ice volume loss of 75% in Swiss glaciers under the RCP4.5 scenario. This is slightly less than the estimates presented in the CH2014-Impacts report (CH2014-Impacts, 2014) for the A1B scenario. Under the RCP8.5 scenario, Swiss glaciers are expected to practically disappear. Glacier retreat will impact hydrology, ecosystems, sediment transport, water quality, landscapes and mountain hazards.
- Water discharge from Swiss glaciers will exhibit an increase in a first phase, followed by a decrease at later stages. "Peak water", i.e. the transition between the two phases, will most likely occur in the first half of the 21st century. Evidence of the increasing phase is provided by gauging stations of highly glacierized basins.
- The future trajectory of water discharge for each glacier, catchment and region is controlled by several factors. While climate projections are usually recognized as the most important source of uncertainty, some physical processes are still poorly understood or insufficiently represented in numerical models. The long-term evolution of debris-covered glaciers and subglacial sediments, the role of englacial and subglacial hydrological processes, or the effects of newly formed proglacial lakes on glacier evolution are amongst the most important research gaps. New monitoring techniques, such as high-resolution remote sensing, UAV-photogrammetry or seismic sensors, have all produced novel datasets that will contribute to fill these gaps.
- Projections for future glacier evolution and water discharge are also strongly affected by present-day glacier characteristics. While some of these have been defined with high accuracy, such as glacier extents for example, others can only be estimated or measured with relatively high uncertainties. Such variables include the spatial distribution of the glacier ice volume, snow accumulation distribution, the debris cover thickness, or distributed ice albedo, for example. A better quantification of such parameters will allow for the uncertainty in future projections to be reduced.
- Correctly translating glacio-hydrological results into impacts affecting water management, energy production, human livelihood, ecosystems or hazards will require the integration of knowledge from other fields. Joint efforts at the boundary between natural and social sciences will become more and more important for translating scientific results into societally-relevant outcomes.

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

- Future water management strategies for glacierized catchments should take into account changes in both total annual water availability and seasonal regimes, as well as more critical low-flow conditions during summer and droughts. Continuous and long-term monitoring of Alpine glaciers will be a necessity for the development of any future water strategy.

- Given the nonlinearity of the climate system, the limitations of current glacier models, and the necessity of casting future projections as possible scenarios, water management strategies must learn to cope with a certain level of uncertainty.
- Reservoirs are likely to play an important role in the future of Alpine water reserves. A significant number of new natural reservoirs will emerge as glaciers continue to retreat and expose new lakes. Engineering these for making them suitable for water management is a possible strategy, but optimizing the operation and increasing the capacity of existing infrastructure will most likely be more efficient and cost effective. Future energy strategies will play a major role in defining the future of newly deglacierizing areas.
- Near real-time, medium-term, and long-range forecasts of glacier mass balance and runoff could become important for optimizing the water management of glacierized catchments. Operational monitoring of glacier-related hazards and anticipation of critical conditions of drought and low-flow, on the other hand, will likely become necessary for preventing important negative aspects. Assimilation of new satellite products and ingestion of improved meteorological forecasts have great potential to advance the development of such systems.

Take-home messages

The close cooperation between public offices, academia, and industry has played a key role in generating knowledge about glacier change and its consequences for hydrology.

Glacier retreat will continue in the Swiss Alps and most of the ice will be lost by the end of the 21st century. While the general patterns and impacts of this retreat are clear, uncertainties in climate scenarios and poorly-understood processes will still require policy makers to deal with considerable uncertainties for future projections. Long-term monitoring programs, new observational capabilities and advances in the understanding of basic processes will, however, allow for these uncertainties to be reduced.

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