Evolution of stream and lake water temperature under climate change

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i. Summary

This report presents past observations and projects the future development of water temperature in Swiss lakes and rivers. Projections are made until the end of the 21st century using the CH2018 climate scenarios. Besides climate change effects on temperature, we also discuss effects on discharge for rivers, and effects on the thermal structure, and specifically the seasonal mixing regime and ice cover of lakes.

Observations over the past 40 years show a clear increase in river temperatures, with a mean trend of 0.33 ± 0.03 °C per decade, corresponding to ~80% of the observed air temperature trend. This warming has been continuous over the last four decades and impacts the health of stream ecosystems (e.g. by favouring the spread of fish diseases) and their services (e.g., the water usage for industrial cooling). The temperature rise is more pronounced in the Swiss Plateau than in the Alps, where snow and glacier melt partially mitigates (for now) the effects of increasing air temperature. Conversely, annual average discharge shows no significant trend.

Similar trends have also been reported for Swiss lakes with mean summer lake surface temperature increasing by 0.40 ± 0.08 °C per decade since the 1950s. This warming trend affects lake stratification. Warm periods may for instance increase the occurrence of deep-water anoxic conditions, as observed during the 2003 heat wave in Lake Zurich. In mild winters, ice cover duration is reduced in alpine lakes, and winter deep mixing is less intense in large-peri-alpine lakes. The mild winter 2006/7 limited, for instance, the seasonal mixing of Lake Constance to about 60 m depths. Effects of warming on lake thermal structure vary within and between regions, due to both lake and watershed characteristics as well as regional climate change patterns.

We simulated the future evolution of stream temperature for 10 catchments in Switzerland for a historical reference period (1990–2000) and two future periods: 2055–2065 (mid-century) and 2080–2090 (end of the century). Results show that the temperature will stabilize by the end of the century for the RCP2.6 scenario (strong CO_2 emission reduction), whereas the warming will accelerate with time for the RCP8.5 scenario (business as usual scenario). This expected warming will have significant impacts on the stream ecosystems. Alpine and lowland catchments will experience a similar annual mean temperature increase but display different seasonal effects. While Swiss Plateau rivers will become warmer both in winter and summer (but more in summer), alpine rivers will experience almost no warming in winter but a strong warming exceeding that of air temperature in summer. This is explained by an abrupt decrease in discharge, and by the soil warming resulting from the absence of snow and thus a lower albedo.

Lake temperature projections are based on one-dimensional, vertically resolved, hydrodynamic simulations for 29 lakes. The simulated lakes cover a wide range of sizes, depths and water quality, and an altitude range from 200 to 1800 m a.s.l. Simulations indicate substantial changes in lake thermal structure for RCP8.5 with surface temperatures increasing on average by 3.3 °C at the end of the 21st century. This increase is limited to 0.9 °C in the mitigation scenario RCP2.6. We identified an altitude-dependent evolution of the durations of summer and winter stratification as well the ice-covered period. Larger changes in stratification duration are expected to occur at higher altitude lakes. Yet, these lakes will still maintain winter stratification and a shortened ice-covered period while lower altitude lakes (below ~1500 m a.s.l.) risk drastic changes in the mixing regime. e.g., a complete loss of the ice cover and winter stratification under the RCP8.5 scenarios. Such changes in the mixing regime may strongly impact lake ecosystems. These low to mid altitude lakes may therefore be considered as the most vulnerable to climate change.

ii. Zusammenfassung

Dieser Bericht beleuchtet die vergangene und zukünftige Entwicklung der Temperaturen in Schweizer Seen und Flüssen. Die Berechnungen bis zum Ende des 21. Jahrhunderts basieren auf den Klimaszenarien CH2018. Neben den Klimaauswirkungen auf die Temperaturen betrachten wir auch die Auswirkungen auf die Abflüsse der Fliessgewässer und auf die thermische Struktur von Seen, insbesondere auf die saisonale Mischung und die Eisbedeckung.

Die Temperaturen der Fliessgewässer sind in den letzten 40 Jahre deutlich angestiegen. Der mittlere Anstieg von 0.33 ± 0.03 °C pro Jahrzehnt entspricht etwa 80% der Zunahme der Lufttemperaturen. Diese kontinuierliche Erwärmung hat negative Folgen für die Flussökosysteme (z.B. Förderung der Ausbreitung von Krankheiten) und auf deren Nutzung (z.B. für die Kühlung von Industrieanlagen). Der Temperaturanstieg ist im Mittelland grösser als in den Alpen, wo Schnee- und Gletscherschmelze die Auswirkungen der höheren Lufttemperaturen (bisher) teilweise kompensieren. Der mittlere Jahresabfluss hat sich hingegen kaum verändert.

Die Oberflächentemperaturen der Schweizer Seen sind seit den 1950er Jahren im Mittel um 0.40 ± 0.08 °C pro Jahrzehnt angestiegen, mit entsprechenden Folgen für das Schichtungsverhalten der Seen. Hitzeperioden können zu vermehrtem Auftreten von Sauerstoffarmut im Tiefenwasser führen, wie bei der Hitzewelle 2003 im Zürichsee beobachtet wurde. In milden Wintern verkürzt sich in alpinen Seen die Dauer der Eisbedeckung, und die grossen Voralpenseen mischen sich weniger tief, der Bodensee im milden Winter 2006/7 zum Beispiel nur bis etwa 60 m Tiefe. Die Auswirkungen auf die thermische Struktur von Seen hängen zudem von den Eigenheiten eines Sees und seines Einzugsgebietes sowie von regionalen Unterschieden der Klimaänderung ab.

Die künftige Entwicklung der Fliessgewässertemperaturen wurde mit einem numerischen Modell in 10 Einzugsgebieten für die Referenzperiode 1990-2000 und für die zwei Perioden 2055-2065 und 2080-2090 simuliert. Im Szenario RCP2.6 (konsequenter Klimaschutz) ergibt sich eine Stabilisierung in der zweiten Hälfte des Jahrhunderts, während sich der Temperaturanstieg im Szenario RCP8.5 (kein Klimaschutz) weiter verstärkt. Diese Erwärmung wird starke Auswirkungen auf die Ökosysteme haben. Der Anstieg ist im Jahresmittel ähnlich für Alpen- und Mittellandflüsse, unterscheidet sich aber saisonal. Im Mittelland nehmen die Temperaturen während des ganzen Jahres zu, am stärksten aber im Sommer. In den alpinen Flüssen ändern sich die Temperaturen im Winter kaum, die Erwärmung im Sommer übertrifft aber diejenige der Lufttemperatur. Verursacht ist dies durch eine starke Abnahme der Sommerabflüsse und eine verstärkte Erwärmung des Bodens und verminderte Rückstrahlung aufgrund der längeren schneefreien Zeit.

Die Seetemperaturen wurden mit einem eindimensionalen, vertikal aufgelösten, hydrodynamischen Modell berechnet, für 29 Seen in einem Höhenbereich von 200 bis 1800 m ü. M. und von unterschiedlicher Grösse, Tiefe und Wasserqualität. Die Simulationen ergeben substantielle Veränderungen in der thermischen Struktur der Seen. Im Szenario RCP8.5 erhöhen sich die Oberflächentemperaturen bis Ende des Jahrhunderts um 3.3 °C, im Szenario RCP2.6 mit Klimaschutz nur um 0.9 °C. Die Auswirkungen auf die Dauer der Sommer- und Winterstagnation und der Eisbedeckung sind besonders stark in hoch gelegenen Seen. Anderseits behalten diese weiterhin eine Winterschichtung und eine kürzere Eisbedeckung, während sich in tiefer gelegenen Seen (unterhalb 1500 m ü. M.) im Szenario RCP8.5 deutliche Veränderungen im Mischungsverhalten ergeben können, mit entsprechenden Folgen für die Ökosysteme. Die Seen in mittleren und tieferen Lagen sind deshalb durch den Klimawandel besonders gefährdet.

iii. Résumé

Ce rapport présente des observations de la température des lacs et rivières suisses ainsi que des projections de l'évolution future de ces températures. Les projections sont effectuées jusqu'à la fin du XXI[e] siècle en utilisant les scénarios de changements climatiques CH2018. Ce rapport ne se limite pas à l'effet du changement climatique sur la température, mais évalue également les effets sur le débit des rivières et sur la structure thermale des lacs, en particulier en ce qui concerne le régime de mélange saisonnier et la couverture de glace.

Les observations effectuées lors des 40 dernières années montrent une augmentation claire de la température des rivières, avec une tendance moyenne de +0.33 ± 0.03 °C par décennie, correspondant à environ 80% de la tendance observée pour la température de l'air. Ce réchauffement a été continu durant les quatre dernières décennies et il impacte la santé des écosystèmes fluviaux (p. ex. en favorisant la transmission de maladies des poissons) et les services (p. ex. l'utilisation des rivières pour le refroidissement dans le secteur industriel). L'augmentation de la température est plus prononcée sur le Plateau que dans les Alpes où la fonte de la neige et des glaciers atténue (pour l'instant) les effets de l'augmentation de la température de l'air. À l'inverse, la moyenne annuelle des débits ne présente aucune tendance significative.

Des tendances similaires sont également reportées pour les lacs suisses ; la température moyenne de la surface des lacs en été a augmenté de 0.40 ± 0.08 °C par décennie depuis les années 1950. Ce réchauffement affecte la stratification thermique des lacs et modifie la santé des ecosystèmes lacustres. Les longues périodes de stratification estivales augmentent par exemple la probabilité d'occurrence de conditions anoxiques en eau profonde, comme cela a été observé lors de la vague de chaleur de 2003 dans le lac de Zurich. Lors des hivers doux, la durée de la couverture de glace est réduite dans les lacs alpins et, dans les grands lacs périalpins, le brassagehivernal n'atteind plus nécessairement le fond du lac. L'hiver doux de 2006/2007 a par exemple limité le mélange hivernal du lac de Constance à environ 60 m de profondeur. Les effets du réchauffement sur la structure thermique des lacs varient au sein et entre les régions en raison des caractéristiques des lacs et des bassins versants, ainsi qu'en raison des spécificités régionales du changement climatique.

L'évolution future de la température des cours d'eau a été simulée pour 10 bassins versants en Suisse pour une période de référence historique (1990-2000) et deux périodes futures : 2055-2065 (milieu du siècle) et 2080-2090 (fin du siècle). Les résultats montrent que la température se stabilisera d'ici la fin du siècle pour les scénarios RCP2.6 (fortes réductions des émissions de CO_2), alors que le réchauffement s'accélérera avec le temps pour les scénarios RCP8.5 (« business as usual »). Ce réchauffement attendu aura des répercussions importantes sur les écosystèmes des cours d'eau. Les bassins versants alpins et de plaine connaîtront une augmentation similaire de la moyenne annuelle de la température, mais présenteront des effets saisonniers différents. Alors que les rivières du Plateau se réchaufferont à la fois en hiver et en été (mais davantage en été), les rivières alpines ne connaîtront pratiquement pas de réchauffement en hiver mais un fort réchauffement en été dépassant celui de la température de l'air. Ceci s'explique par une diminution importante du débit en été, ainsi que par le réchauffement des sols résultant de l'absence de neige causant une diminution de l'albédo.

Les projections de la température des lacs sont basées sur des simulations hydrodynamiques unidimensionnelles de 29 lacs. Ces lacs simulés couvrent une large gamme de taille, de profondeur et de qualité de l'eau, et une plage d'altitude allant de 200 à 1800 m au dessus du

niveau de la mer. Les simulations indiquent des changements substantiels dans la structure thermique des lacs pour les scénarios RCP8.5, avec des températures de surface augmentant en moyenne de 3.3 °C à la fin du 21e siècle. Cette augmentation est limitée à 0.9 °C avec les scénarios RCP2.6. Les durées de la stratification estivale et hivernale ainsi que de la période de couverture de glace montrent une tendance univoque en fonction de l'altitude. Les changements les plus importants de durée de stratification devraient se produire dans les lacs de plus haute altitude. Cependant, ces lacs devraient conserver tout au long du XXI^{e} siècle une stratification hivernale et une période de couverture de glace raccourcie. Les lacs de plus basse altitude (en dessous de ~1500 m d'altitude) risquent eux de subir des changements drastiques du régime de brassage avec, par exemple, une perte complète de la couverture de glace et de la stratification hivernale pour les scénarios RCP8.5. De tels changements du régime de mélange auront un impact fort sur les écosystèmes lacustres. Ces lacs Suisse de faible à moyenne altitude peuvent donc être considérés comme les plus vulnérables au changement climatique.

iv. Table of contents

v. List of abbreviations and definitions

CC	Climate Change
CH2011	Swiss Climate Change Scenarios 2011
CH2018	Swiss Climate Change Scenarios 2018 with additional RCM and variables
DOY	Day Of the Year
FOEN	Federal Office for the Environment (BAFU)
GCM	Global Circulation Model
GCOS	Global Climate Observation System
KGE	Klinge-Gupta Efficiency
MSE	Mean Square Error
NCCS	National Center for Climate Services
PKD	Proliferative Kidney Disease
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RMSE	Root Mean Square Error
Swiss Plateau	Region between the Jura and the Alps, a.k.a. “Schweizer Mittelland”
1D model	One-dimensional numerical model
3D model	Three-dimensional numerical model

1 Introduction

Switzerland is often viewed as the "water tower" of Europe with a variety of water systems. Lakes cover 3.5 % of the area of Switzerland divided into ~1600 water bodies larger than 0.5 ha. River systems are also very abundant in Switzerland; they originate from the Swiss Alps and are feeding into the Mediterranean See, the North See, and the Black See through the main rivers of Western Europe. This easily accessible resource of freshwater is increasingly under pressure by climate change (CC) affecting its thermal structure and finally impacting the ecosystems. This report presents observations and projections of the future development of water temperature in Swiss lakes and rivers. Projections are made until the end of the 21st century under the CH2018 climate scenarios. Besides temperature, rivers discharge is also discussed (note that a similar report dedicated to discharge has also been produced in the framework of this project (Mülchi et al., 2020)), and the investigation of lakes also includes seasonal mixing and ice cover.

Stream temperature is expected to be impacted by CC, mainly through the influence of the rising air temperature, changes in precipitation, and changes in the hydrologic regime, especially snowmelt. Changes in the hydrologic regime are expected to lead to more frequent and longer duration low flow conditions, which typically amplify stream water warming. At global scale and at the scale of Switzerland, the projections of air temperature rise are clear and significant (Kirtman et al., 2013; Collins et al., 2013; CH2018, 2018). Several studies have shown clear trends in the last decades in lake surface temperature (O'Reilly et al., 2015, Woolway et al., 2017), and in stream temperature at various locations worldwide (Morrison et al., 2002; Webb and Nobilis, 2007; FOEN, 2012; Hannah and Garner, 2015; Watts et al., 2015). At all locations, these studies predict a future rise of water temperatures, with various ranges depending on the specific location.

Earlier studies on the impacts of CC on Swiss lakes and rivers, e.g. FOEN (2012), have already observed an increase in stream temperatures, but included only qualitative statements about future CC impact on rivers. This Hydro-CH2018 report uses a quantitative approach for assessing CC impacts on water temperature in both rivers and lakes. First, a comprehensive analysis of historical stream and lake temperature data up to 2018 was used to evaluate recent perturbations of the system. Numerical models provided then a tool to estimate trends in lake and river warming for different periods of the 21st century driven by meteorological forcing from three CC scenarios (RCP8.5, RCP4.5, and RCP2.6) with unprecedented downscaled bias reduction.

1.1 Stream temperature

1.1.1 Factors governing stream temperature

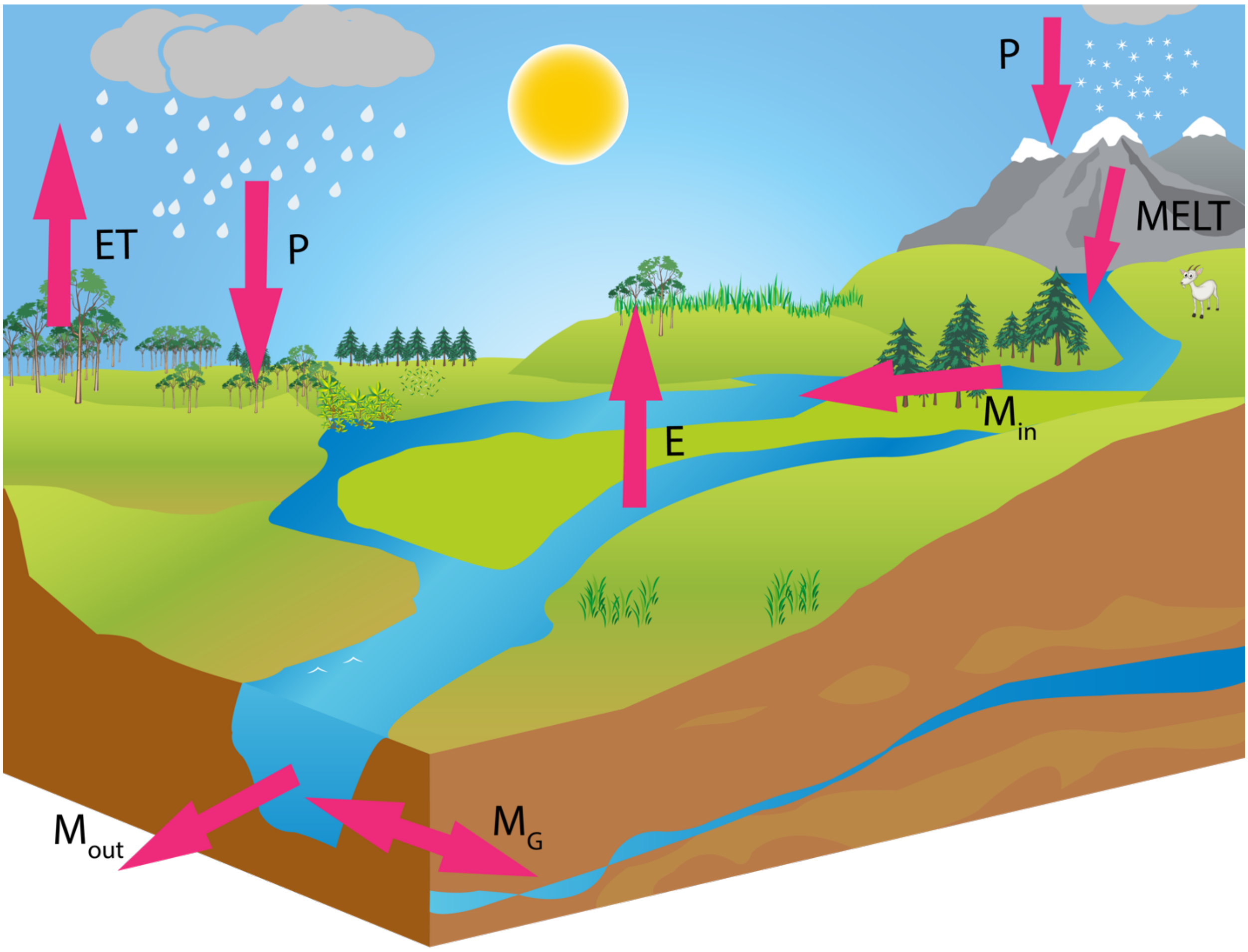
Discharge and thermodynamics of fluvial systems are influenced by the climate conditions to which they are exposed and are obviously subject to change when a shift or alteration in these climate conditions occurs. The temperature of streams is determined by different variables and conditions (which might be interdependent), such as heat and mass fluxes at the boundaries of the water body, geomorphology of the stream bed, riparian vegetation and surrounding land cover, as well as headwater conditions, discharge and flow velocity, ground water exchange, and finally to an increasingly large extent by anthropogenic impacts. The main components of the mass and energy balance governing streams are presented in Figures 1 and 2. With CC, the main factor expected to change are air temperature and river discharge (due to changes in precipitations, in evapotranspiration and in snow and glacier cover) and to a lesser extent solar radiation.

From a general perspective, the main control on water temperature is air temperature, with a more or less pronounced non-linear relationship at sub-yearly scale (such relationships often show typical seasonal hysteresis; Morrill et al., 2005), but with a linear relationship on longer time scales (Lepori et al., 2015a; Michel et al., 2020), whereby the linear regression slope depends on the characteristics of the respective catchment. The heat flux at the water surface is the sum of the net solar shortwave radiation, the net longwave radiation, the evaporative flux (latent heat) and the convective heat transfer (sensible heat). The friction due to motion of water at the streambed as well as conductive streambed/water heat exchanges have been shown to be non-negligible components is some cases (Webb and Zhang, 1997; Moore et al., 2005; Caissie, 2006; Küry et al., 2017), especially for steep slope rivers with high flow velocity. These heat sources are more important in the total heat budget in autumn (when residual heat from summer is still stored in the ground) and when riparian vegetation is present (because of shading and reduced wind velocity, which reduce surface heat fluxes). Depending on the climatic region, all of the above heat fluxes show a moderate or strong seasonality, which induces a seasonally varying relative dominance of some of the acting heat fluxes resulting in a corresponding seasonally varying impact on the stream temperature. In most cases, incoming solar and longwave radiation remain the most important contribution, while at night time, heat loss due to longwave radiation prevails.

Ground water temperature is also an important factor, especially in stream reaches close to the source (Caissie, 2006). This may apply in particular to high alpine rivers in Switzerland which are often glacier- or snow-fed, and thus sensitive to changes in the amount of melt water release as well as to changes in the seasonality of soil temperature (Harrington et al.,2017; Küry et al., 2017). Discharge has also an important non-linear influence on water temperature (Caissie, 2006; Webb and Nobilis, 2007; Toffolon and Piccolroaz, 2015; Michel et al., 2020), and the temperature change resulting in a stream from a change in the heat fluxes is directly related to the stream discharge. This is the reason why the present study, in spite of being focused on water temperature, also discusses observed and predicted discharge changes.

Anthropogenic influence on stream temperature has been observed as a result of vegetation removal (Johnson and Jones, 2000; Moore et al., 2005) urbanization and stream channelization (Webb, 1996; Lepori et al., 2015a), use of water for industrial cooling (Webb,1996; Råman Vinnå et al., 2018) or extensive use for agriculture (Caissie, 2006). Hydropeaking (release of water at sub-daily time scale from hydropower plants) has been shown to reduce the impact of summer heatwaves on water temperature due to the injection of cold water from reservoirs at higher elevation (Feng et al., 2018; Michel et al., 2020). Human influence on rivers through thermal pollution has also been shown to modify the relationship between air and water temperature, leading to a weaker correlation (Webb et al., 2008). These influences must be taken into consideration when studying the impact of CC in anthropogenically modified and perturbed catchments (Webb et al., 2008, Hannah and Garner, 2015; Råman Vinnå et al., 2018).

MASS FLUXES



P: Precipitation (liquid or solid)
MELT: Snow and glacier melt
E: Evaporation from water body
ET: Evapotranspiration from soil and vegetation

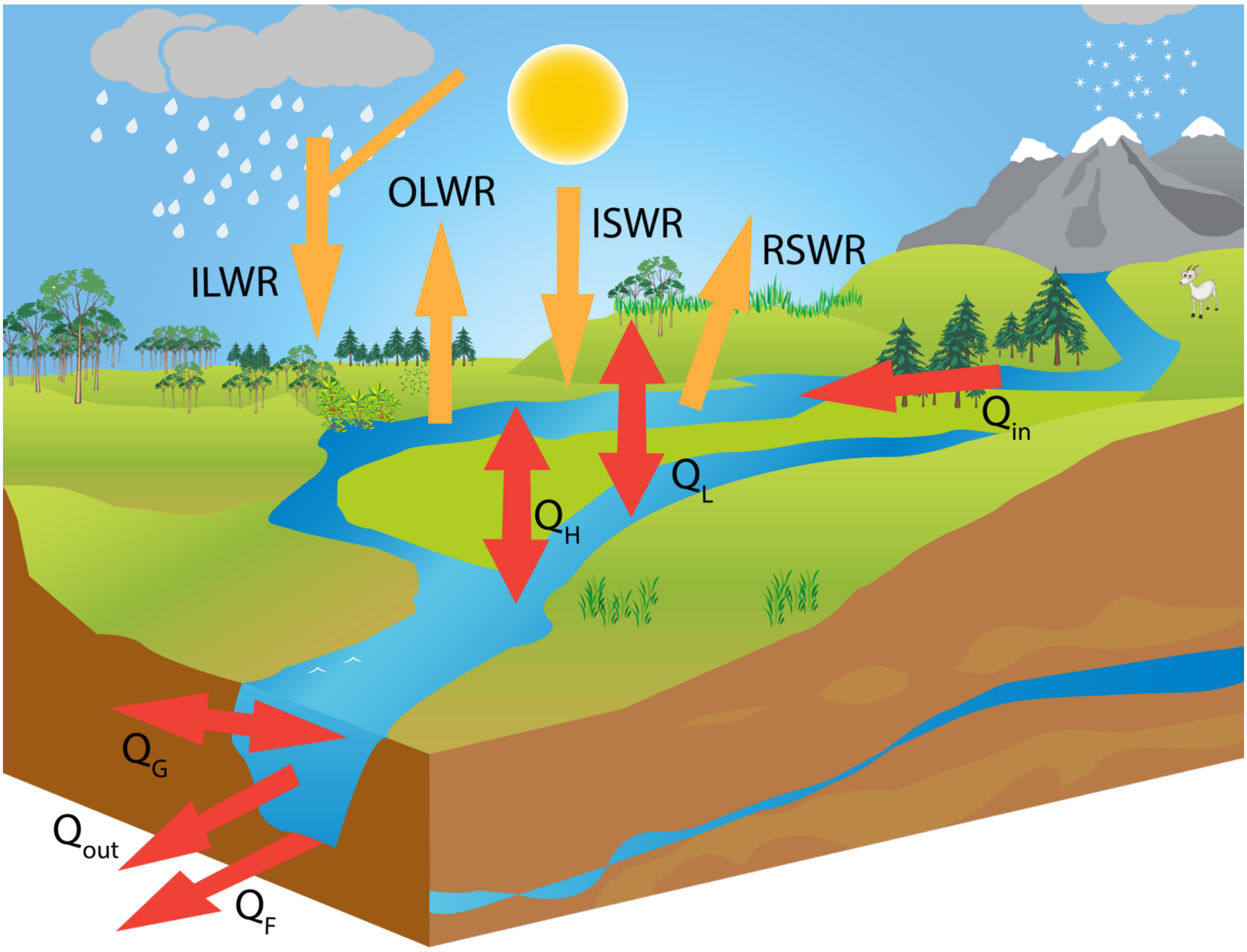
M_{IN}: Incoming upstream water
M_{OUT} : Outgoing downstream water
M_G: Water ex/infiltration from/to groundwater

Figure 1. Main mass fluxes governing stream discharge. (Figure using visuals from vecteezy.com)

Since local hydrological characteristics contribute to stream temperature, differences between catchments will affect the reaction to environmental and/or CC. For example, at small spatial scales such as alpine springs, e.g. in the Swiss Alps, factors like presence of snow or permafrost, elevation, aspect, or geology, which all exhibit high spatial variability, will have a large influence on the temperature of the water entering the river network (Küry et al., 2017).

Here we investigate the impact of CC over the past decades for 52 catchments in Switzerland (Section 2.1) and use physical models to assess the future evolution of stream temperature over ten catchments for the periods 2055–2065 and 2080–2090 (Section 2.3).

ENERGY FLUXES



RADIATIVE HEAT FLUXES

ISWR : Incoming shortwave radiation (direct from the sun and diffuse from the sky)

ILWR : Incoming longwave (infrared) radiation from the sky (mainly clouds)

RSWR : Reflected shortwave radiation

OLWR : Outgoing longwave (infrared) radiation emitted by the ground and water body

NON-RADIATIVE HEAT FLUXES

Q_G : Heat exchange with the ground (conduction)

Q_{IN} : Heat advected from upstream reach

Q_{OUT} : Heat advected to downstream reach

Q_H : Sensible heat (heat exchange with the air)

Q_L : Latent heat (evaporation and condensation)

Q_F : Heat produced by friction

Figure 2. Main energy fluxes governing stream temperature. (Figure using visuals from vecteezy.com)

1.1.2 Stream temperature modelling

Projections regarding the impact of CC on stream temperatures have to rely on models; the uncertainties related to such hydrological projections and predictions is rather large. Part of the uncertainty arises from the natural variability of the water regime and models will always be subject to that (Fatichi et al., 2016). However, a significant part of the uncertainty arises from the representation of relevant physical processes in these models. Uncertainty can therefore be reduced by using more precise and physically accurate models (Gurtz et al., 2005; Prudhomme et al., 2014; Comola et al., 2015; Giuntoli et al., 2015a,b). In addition, a large uncertainty based on the future greenhouse gas emission pathway exists.

A large number of models has been developed to predict water discharge, temperature, or both. Several reviews of such models exist in the literature (e.g. Benyahya et al. 2007; Gallice et al., 2015). The existing models are generally grouped into two main families: statistical or physical models. Statistical models rely on statistical (linear or not) relations to reproduce the variables of interest based on available input data. Most of them are based on measured air temperature data. They require an extensive calibration phase (or learning phase in case neural-network models are used), and calibrated model might be not valid outside of the observed temperature range. On the other hand, physically based models use a physical formulation of the mass and/or energy conservation to reproduce discharge and/or temperature. These models require generally more input data than the statistical models and are significantly more demanding in terms of computation. Today, quite complete physically based models are available; however, these are usually less used since the many and spatially distributed input variables are not always available to drive such models. These models are usually not limited to simple water routing but have to consider water input, e.g. precipitation, atmospheric energy fluxes, snow and glacier melt, water flow in the ground, and if available even ground water processes.

There are only a few coupled physical hydro-thermal models resolving discharge and temperature at the same time (a review of these models can be found in the work of Gallice et al. (2016)). Most of the few available coupled models use the statistical degree-day method to simulate snowmelt and ensuing surface and subsurface runoff, which shows generally reasonable results. However, a more physical representation of the snow processes in space and time or of water percolation processes could improve snow runoff modelling, which is important in some catchments (Martin and Etchevers, 2005; Lisi et al., 2015; Brauchli et al., 2017, Griessinger et al., 2019).

These considerations and limitations motivated the development of a new semi-distributed, coupled physical model called *StreamFlow*, particularly for seasonally snow-covered mountain regions. This model is combined with the physical snow–soil–vegetation model *Alpine3D* (Lehning et al., 2006) to model the snow cover evolution in great detail. A first version of the model was presented in the work of Comola et al. (2015), using a two linear reservoirs model for water retention in the soil, and solving the mass and energy balance (for stream and soil water) at every time step. The model works at a sub-watershed scale, i.e. each sub-watershed and sub-reach is represented as one point feeding the stream network. The model was significantly enhanced by Gallice et al. (2016), featuring a better integration with *Alpine3D*, allowing a discrete representation of the stream reaches, and adding different modules to compute the water temperature.

In the present project, *StreamFlow* and *Alpine3D* have been further enhanced, mostly in terms of computational performance in order to allow the simulation of larger catchments. In addition, better calibration routines for the residence time of the water in the soil have been added to *StreamFlow*, and the soil parametrization along with the parametrization of glacier melt have been enhanced in *Alpine3D*.

1.1.3 Human-built infrastructure in models

Many current hydrological models, including *StreamFlow*, do not consider human influences, neither in terms of water use, nor in terms of energy addition or removal. However, these two variables have been shown to become increasingly important (Biemans et al., 2011; Råman Vinnå et al., 2018) and it is difficult to find large river systems in Switzerland with little or without any human impact. Large infrastructures, especially dams, which are very abundant in Switzerland, are challenging elements to represent in models. Indeed, for dams, some reservoir modelling is required and the entire system of water routing and pumping across the simulation area must be implemented. Moreover, operational information on the pumping system and on the water management must be known, but these are usually not available from the operator. Finally, there is large uncertainty regarding the management of dams in the future. Indeed, their management might change over the next decades in the context of the planned energy transition in Switzerland, and especially in light of the emergence of increased solar power production (Manso et al., 2015; Dujardin et al., 2017) and the increasing trends towards multipurpose reservoir management (NFP61, 2015; Kellner, 2019). CC itself is also expected to influence hydro-power production and dam operations (Schaefli et al., 2007; Farinotti et al., 2016, SCCER-SoE, 2019).

Since these disturbances cannot be included in the model used, only catchments with no or minor disturbances are used for the CC study presented in Section 2.3.

1.2 Lake temperature

1.2.1 Seasonality

Lake surface temperature shows a well-known temperature cycle over the year in Switzerland with cold temperature in winter and warm temperature in summer. This cycle directly results from the seasonally changing heat exchange at the surface of lakes. Those exchanges can be divided into penetrative (solar or shortwave radiation) and non-penetrative (longwave radiation, latent and sensible) heat fluxes. Most of the heat is stored during summer in the very top layers, creating a gradient in energy storage which leads to a vertical temperature and density gradient (thermocline) separating the warm surface water (epilimnion) from the cold deep water (hypolimnion). The thermocline limits the exchange between the surface and the deep water through diffusion and advection, effectively keeping the two water bodies separated. The fall season is characterized by a net heat loss resulting in a gradual cooling of the surface water and for most lakes a homogenization (i.e. deep mixing) of the water column. In cold areas such as alpine regions, lake surface temperature may decrease below the temperature of maximum density (~4 °C), and an inverse winter stratification forms, separating again the deep water from the now colder surface water. The surface water may ultimately reach the freezing temperature leading to ice formation. Finally, in spring, increasing solar radiation and air temperature revert the net heat flux, melt the ice, and again warm the surface layer.

Lakes are often characterised by their mixing regime. Lakes that are vertically homogenised twice a year through deep mixing (in fall and in spring) and feature both summer and inverse winter stratification are called dimictic. Warm monomictic lakes are homogenised only once in winter and do not develop an inverse stratification. Lakes that are never or only rarely completely homogenised, are called meromictic, lakes with occasional complete mixing every few years are called oligomictic, and shallow lakes that are homogenised frequently throughout a year are called polymictic.

1.2.2 Beyond temperature: assessing thermal structure

The effects of CC on lakes are more complex than their sole manifestation on changes in the surface temperature, and effects of warming vary within and between regions. This spatial heterogeneity results from both lake and watershed characteristics as well as regional variabilities in CC patterns. A full assessment of the evolution of the thermal structure over the entire water column is needed to evaluate the effect of CC on lakes. This requires the quantification and analysis of additional parameters such as (i) the strength and duration of summer thermal stratification, (ii) the duration of inverse stratification and ice-cover in winter, and (iii) the frequency and intensity of deep seasonal mixing, which defines the mixing regime of a lake. Changes in the thermal structure are caused by three processes:

1. Long term trends in atmospheric forcing - Traditionally, the focus has been put on assigning a lake's response to a gradual long-term warming over time by analysing long time series of in situ temperature data (Adrian et al., 2009; Lemmin and Amouroux, 2006; Livingstone, 2003) together with trends in climate variables (Schwefel et al., 2016; Schmid et al., 2014; Perroud and Goyette, 2010). In general, for Swiss lakes, a warming trend of the surface layer of ~0.4 °C per decade has been observed (see also Table 8 in Section 3.2.1). Long term changes in the heat fluxes are the main driving force explaining the observed alterations in the thermal structure of lakes, and the discussion of these processes therefore form the core of the present report. Two other type of perturbations are however briefly mentioned below.

2. Changes in frequency and distribution of extreme events such as heat waves, floods, and storms - Beside the gradual change in atmospheric forcing, frequency and distribution of extreme events have also changed (Pachauri et al., 2015). For Switzerland, an increase of warm extremes, a decrease of cold extremes and an increase in precipitation extremes is expected (Pachauri et al., 2015; CH2018, 2018). Jankowski et al. (2006) exemplarily evaluated the impact of the 2003 heat wave on Lake Zurich, and proposed that increased frequency of extremely warm periods may lead to increasingly frequent anoxic conditions in the hypolimnion of deep lakes. Straile et al. (2012) showed that the extraordinarily mild winter 2006/7 prevented the seasonal mixing of Lake Constance from reaching depths >60 m. Climatically induced alteration of the distribution and occurrence rate of extreme events can locally be more influential than the long-term effect of gradual temperature increase (Perga et al., 2018; Kasprzak et al., 2017).

3. Changes in discharge or temperature of inflows due to modifications in the upstream watershed, often impacted in addition by anthropogenic point sources of heat or affected by discharge regulation - Temperatures of inland waters are affected by alterations in the watershed also modified by anthropogenic pressure and CC. In some lakes, anthropogenic thermal loads can have similar importance as CC on the evolution of the thermal structure. An example is Lake Biel, where temperature is increased on average by ~0.3 °C and locally by up to 3.4 °C by the heat input of an upstream nuclear power plant (Råman Vinnå et al., 2017, 2018). In alpine regions, glacier retreat and permafrost melting modify the type of organic and inorganic particles entering into lakes, which, in turn, affects lake turbidity and light penetration and finally the thermal structure (Peter and Sommaruga, 2017). Glacier retreat also modifies the timing, magnitude, and frequency of downstream discharge (Milner et al., 2017) which can affect the thermal structure of downstream lakes.

In the following, we present the main external forcing factors responsible for a change in the thermal structure of lakes and then discuss how the characteristics of a lake modify its response to this forcing. How heat fluxes and internal processes in Swiss lakes are projected to change in the 21st century is summarized in Figure 3.

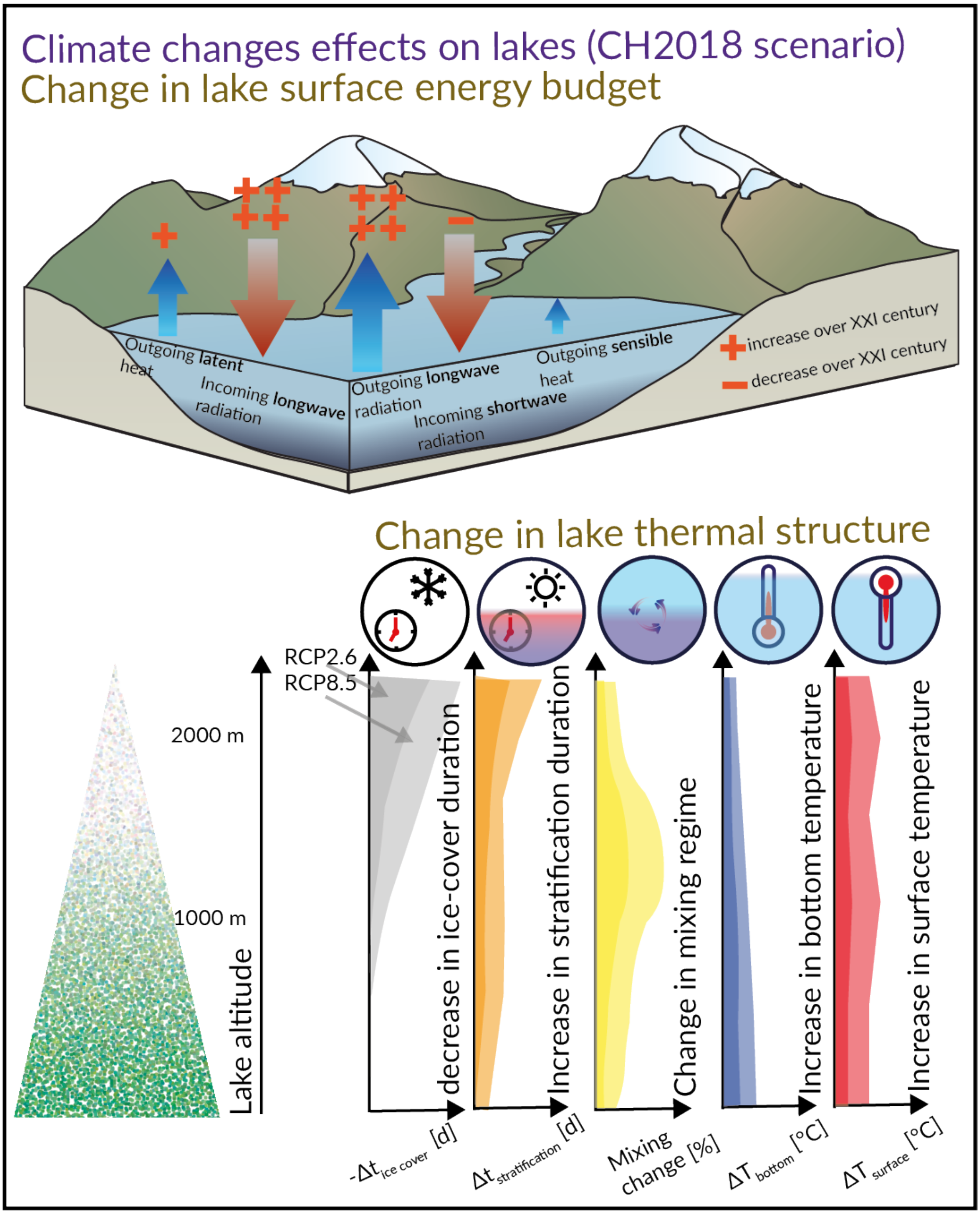


Figure 3. Schematic of processes affected by and affecting the reaction of lakes to CC under climate scenarios RCP8.5 and RCP2.6. Top frame: heat fluxes into lakes where plus and minus signs show heat flux changes over the 21st century. Bottom frames: qualitative representation of the altitudinal dependence of projected changes of the thermal structure of in Swiss lakes considered in this report. For further details, see Sections 3.3 and 3.4.

2 Water temperature of streams

2.1 Observed stream temperature changes and their causes

At global scale, several studies have shown a clear trend over the last decades in lake surface temperature (Dokulil, 2014; O'Reilly et al., 2015, Woolway et al., 2017), and in stream temperature at various locations (Morrison et al., 2002; Hari et al., 2006; Webb and Nobilis, 2007; Null et al., 2013; Ficklin et al., 2014; Hannah and Garner, 2015; Watts et al., 2015; Santiago et al., 2017; Jackson et al., 2018). In Switzerland, some changes in seasonal discharge and in extreme events have already been observed over the past decades, but not necessarily with a direct attribution to CC (Birsan et al., 2005; Schmocker-Fackel and Naef, 2010; Kormann et al., 2016, Rottler et al., 2020). The same conclusion applies for the observed changes in precipitation (Masson and Frei, 2016).

In the framework of the present project, a comprehensive analysis of observed stream temperature based on all data available in Switzerland has been carried out (Michel et al., 2020). The main results are summarized in this section, and readers are referred to the related journal paper for more details. The influence of discharge, precipitation, air temperature, and upstream lakes on stream temperatures and their temporal trends have been analysed from multi-decadal to seasonal time scales for 52 catchments in Switzerland (Figure 4 and Table 1). Trends are computed with linear regressions performed on de-seasonalized time series (using the STL algorithm described in Cleveland et al.,1990) for the periods 1979–2018 and 1999–2018. We show that stream temperature has significantly increased over the past four decades (Figure 5), with positive trends in all four seasons (Tables 2 and 3).

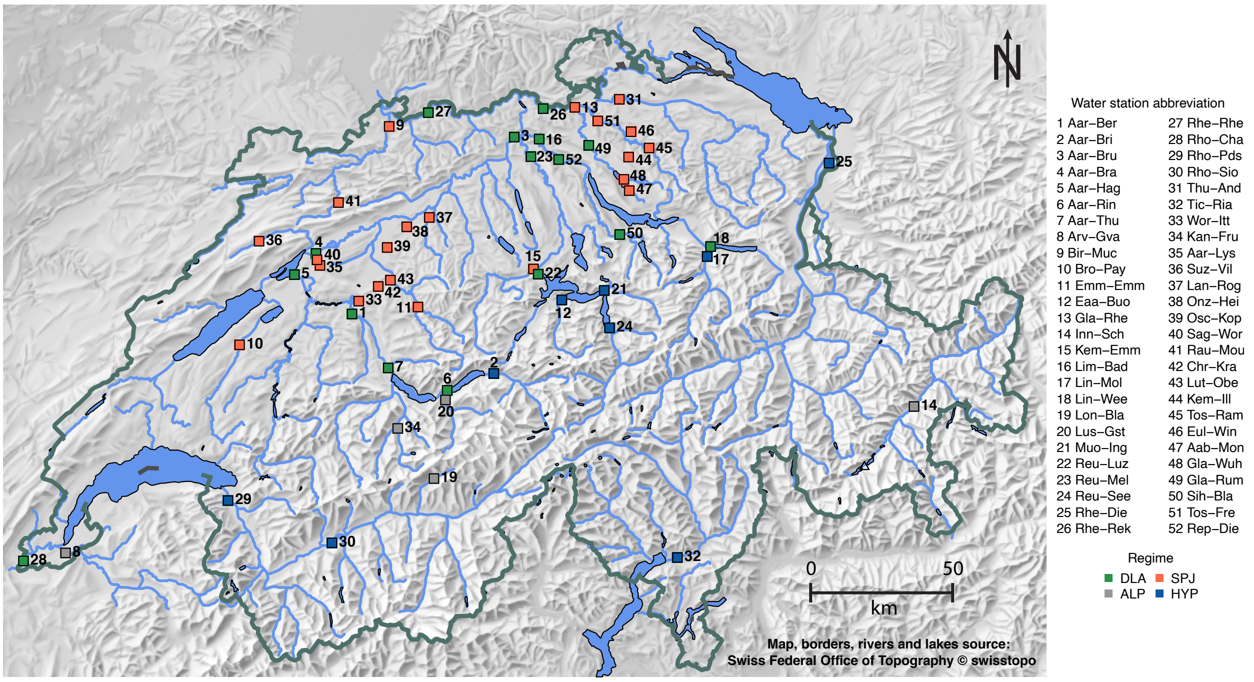


Figure 4. Map of Switzerland showing the selected hydrometric gauging stations. Abbreviations for hydrometric gauging stations are defined in Table 1, and abbreviations for catchment types are as follows: DLA represents the downstream lake regime, ALP represents the alpine regime, SPJ represents the Swiss Plateau/Jura regime, and HYP represents catchments with strong influence from hydro-peaking. Figure from Michel et al. (2020).

Table 1. Characteristics and data availability for water temperature and discharge of the 52 selected catchments. The IDs are those used by the data providers. The providers are the Swiss Federal Office for the Environment (FOEN), the Canton of Bern Office of Water and Waste Management (AWA), and the Canton of Zurich Office of Waste, Water, Energy and Air (AWEL). Table from Michel et al. (2020).

ID	River	Abbreviation	Temperature measurement	Discharge measurement	Area (km^2)	Mean alt. (m)	Glacier (%)	Data provider
527	Aabach in Mönchaltorf	Aab-Mon	1992–2018	1992–2018	46	523	0	AWEL
2135	Aare in Bern	Aar-Ber	1971–2018	1918–2018	2941	1596	5.8	FOEN
2019	Aare in Brienzwiler	Aar-Bri	1971–2018	1905–2018	555	2135	15.5	FOEN
2016	Aare in Brugg	Aar-Bru	1963–2018	1916–2018	11681	1000	1.5	FOEN
2029	Aare in Brügg–Aegerten	Aar-Bra	1963–2018	1989–2016	8249	1142	2.1	FOEN
2085	Aare in Hagneck	Aar-Hag	1971–2018	1984–2018	5112	1368	3.4	FOEN
2457	Aare in Ringgenberg	Aar-Rin	1964–2018	1931–2016	1138	1951	12.1	FOEN
2030	Aare in Thun	Aar-Thu	1971–2018	1906–2018	2459	1746	6.9	FOEN
A019	Alte Aare in Lyss	Aar-Lys	1997–2018	1997–2018	13	462	0	AWA
2170	Arve in Geneva	Arv-Gva	1969–2018	1904–2018	1973	1370	5	FOEN
2106	Birs in Münchenstein	Bir-Muc	1972–2018	1917–2018	887	728	0	FOEN
2034	Broye in Payerne	Bro-Pay	1976–2018	1920–2018	416	715	0	FOEN
A062	Chrouchtalbach in Krauchthal	Chr-Kra	1999–2018	1999–2018	16	702	0	AWA
2070	Emme in Emmenmatt	Emm-Emm	1976–2018	1974–2018	443	1065	0	FOEN
2481	Engelberger Aa in Buochs	Eaa-Buo	1983–2018	1916–2018	228	1609	2.5	FOEN
522	Eulach in Winterthur	Eul-Win	1993–2018	1993–2018	64	541	0	AWEL
2415	Glatt in Rheinfelden	Gla-Rhe	1977–2018	1976–2018	417	503	0	FOEN
534	Glatt in Rümlang	Gla-Rum	1992–2018	1992–2018	302	520	0	AWEL
531	Glatt in Wuhrbrücke	Gla-Wuh	1993–2018	1993–2018	64	621	0	AWEL
2462	Inn in S-Chanf	Inn-Sch	1981–2018	1999–2018	616	2463	6.1	FOEN
A017	Kander in Frutigen	Kan-Fru	1995–2018	1992–2018	180	2156	14	AWA
517	Kempt in Illnau	Kem-Ill	1992–2018	1992–2018	37	615	0	AWEL
2634	Kleine Emme in Emmen	Kem-Emm	1973–2018	1936–2018	478	1054	0	FOEN
A025	Langete in Roggwil	Lan-Rog	1996–2018	1996–2018	130	689	0	AWA
2243	Limmat in Baden	Lim-Bad	1969–2018	1951–2018	2384	1131	0.7	FOEN
2372	Linth in Mollis	Lin-Mol	1964–2018	1914–2018	600	1743	2.9	FOEN
2104	Linth in Weesen	Lin-Wee	1964–2018	1907–2018	1062	1584	1.6	FOEN
2269	Lonza in Blatten	Lon-Bla	1967–2018	1956–2018	77	2624	24.7	FOEN
A070	Luterbach in Oberburg	Lut-Obe	1994–2018	1994–2018	34	700	0	AWA
2109	Lütschine in Gsteig	Lus-Gst	1964–2018	1908–2018	381	2050	13.5	FOEN
2084	Muota in Ingenbohl	Muo-Ing	1974–2018	1917–2018	317	1363	0	FOEN
A029	Önz in Heimenhausen	Onz-Hei	1994–2018	1995–2018	86	582	0	AWA
A031	Ösch in Koppigen	Osc-Kop	1997–2018	1997–2018	39	559	0	AWA
A049	Raus in Moutier	Rau-Mou	1997–2018	1997–2018	41	896	0	AWA
572	Reppisch in Dietikon	Rep-Die	1993–2018	1993–2018	69	594	0	AWEL
2152	Reuss in Luzern	Reu-Luz	1973–2018	1922–2018	2254	1504	2.8	FOEN
2018	Reuss in Mellingen	Reu-Mel	1969–2018	1904–2018	3386	1259	1.8	FOEN
2056	Reuss in Seedorf	Reu-See	1971–2018	1904–2018	833	2013	6.4	FOEN
2473	Rhein in Diepoldsau	Rhe-Die	1970–2018	1919–2018	6299	1771	0.7	FOEN
2143	Rhein in Rekingen	Rhe-Rek	1969–2018	1904–2018	14767	1131	0.4	FOEN
2091	Rhein in Rheinfelden	Rhe-Rhe	1971–2018	1933–2018	34524	1068	1.1	FOEN
2174	Rhône in Chancy	Rho-Cha	1971-2017	1904–2017	10308	1569	8.3	FOEN
2009	Rhône in Porte du Scex	Rho-Pds	1968–2018	1905–2018	5238	2127	11.1	FOEN
2011	Rhône in Sion	Rho-Sio	1974–2018	1916–2018	3372	2291	14.2	FOEN
A047	Sagibach in Worben	Sag-Wor	1996–2018	1996–2018	13	459	0	AWA
547	Sihl in Blattwag	Sih-Bla	1992–2018	1992–2018	102	1168	0	AWEL
A022	Suze in Villeret	Suz-Vil	1995–2018	1995–2018	61	1080	0	AWA
2044	Thur in Andelfingen	Thu-And	1963–2018	1904–2018	1702	770	0	FOEN
2068	Ticino in Riazzino	Tic-Ria	1978–2017	1997–2018	1613	1643	0.1	FOEN
570	Töss in Freienstein	Tos-Fre	1992–2018	1992–2018	399	626	0	AWEL
520	Töss in Ramismuhle	Tos-Ram	1992–2018	1992–2018	127	803	0	AWEL
2500	Worble in Ittigen	Wor-Itt	1989–2018	1989–2018	67	666	0	FOEN

The mean water temperature trend for the last 2 decades (2000–2018) is +0.37 ± 0.11 °C per decade, resulting from the joint effects of trends in air temperature (+0.39 ± 0.14°C per decade), discharge (−10.1 ± 4.6 % per decade), and precipitation (−9.3 ± 3.4 % per decade). For a longer time period (1979–2018, for the catchments where enough data are available), the observed trends are +0.33 ± 0.03 °C per decade for water temperature, +0.46 ± 0.03 °C per decade for air temperature, −3.0 ± 0.5 % per decade for discharge, and −1.3 ± 0.5 % per decade for precipitation. All the trends in water temperature and discharge for the two time periods and for each individual catchment are presented in Tables 2 and 3. Uncertainty values on trend are obtained by computing trends with 2 years removed at the beginning or end of the time series, the biggest difference in obtained trends is taken as uncertainty.

Trends of discharge and precipitation over the last 20 and 40 years differ significantly. A decrease of 10 % per decade has been observed over the 1999–2018 period. This decrease is more evident in spring and autumn and comparably small in winter. The annual discharge evolution is closely related to the annual precipitation evolution. Considering longer period, there are some oscillations in the observed discharge and precipitation time series, and mean discharge similar to today's values were already observed in the past. Therefore, it is not currently possible to assess whether there is a tangible impact from CC on discharge at the country scale in Switzerland.

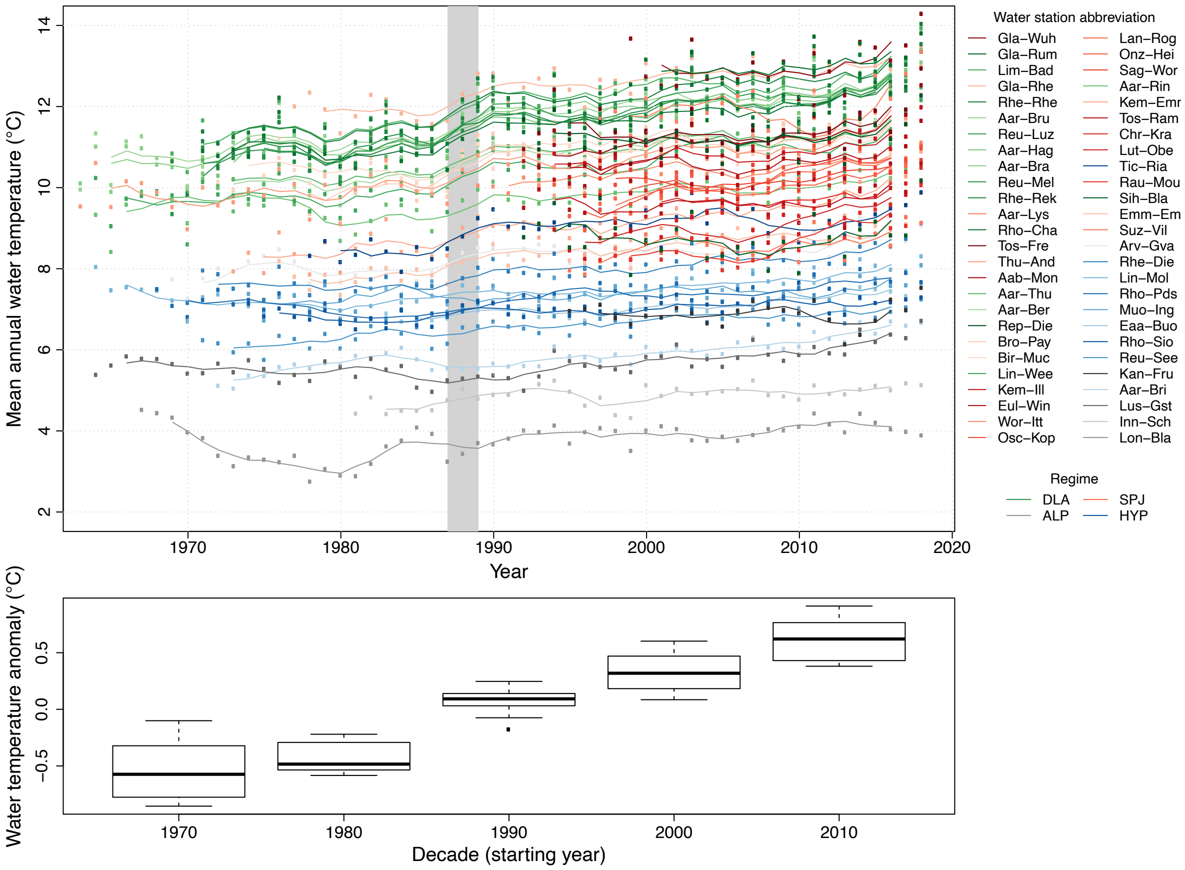


Figure 5. Top: Mean annual stream temperature of the 52 catchments described in Table 1. Lines show the 5-year moving averages. Colours indicate the hydrological regimes. Streams names are ordered by temperature in the last year (from high to low). The 1987/1988 transition period is highlighted using grey. Abbreviations for river names are given in Table 1. Bottom: Water temperature anomalies per decade with respect to the 1970–2018 mean, for the 14 catchments with data available since 1970. Thick lines are the median and red dots the mean values. Boxes represent the first and third quartiles of the data, whiskers extend to points up to 1.5 times the box range (i.e. up to 1.5 times the distance of the first to third quartiles) and extra outliers are represented as circles. Figure from Michel et al. (2020).

Table 2. Water temperature (left section) and discharge (right section) annual and seasonal trends for all catchments presented in Table 1 over the 1999–2018 period. The numbers in parentheses indicate the standard error of the computed trends based on linear regression. Table from Michel et al. (2020).

Name	Water temperature trend (°C per decade)					Discharge trend (% per decade)				
	Annual	Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn
Aar-Ber	0.35 (0.12)	0.10 (0.07)	0.20 (0.05)	0.62 (0.23)	0.47 (0.14)	−5.9 (3.8)	5.7 (10.8)	−9.8 (10.2)	−6.9 (2)	−7.1 (2.2)
Aar-Bra	0.44 (0.08)	0.28 (0.13)	0.26 (0.11)	0.69 (0.23)	0.54 (0.08)	−6.8 (4.4)	6.5 (0.3)	−17.8 (10)	−0.8 (3.7)	−9.5 (0.8)
Aar-Bri	0.44 (0.02)	0.29 (0.02)	0.17 (0.01)	0.80 (0.10)	0.47 (0.06)	−4.6 (2.8)	−4.6 (9.4)	−5.4 (6.7)	−6.1 (1.5)	−1.3 (2.7)
Aar-Bru	0.44 (0.12)	0.29 (0.11)	0.32 (0.12)	0.60 (0.27)	0.50 (0.11)	−9.4 (3.2)	6.8 (9.8)	−16.5 (7.7)	−7.4 (3.7)	−19.2 (4.6)
Aar-Hag	0.58 (0.11)	0.20 (0.15)	0.47 (0.15)	0.92 (0.26)	0.72 (0.19)	−4.5 (4.6)	13.5 (11)	−10.4 (10.7)	−6.4 (3.1)	−8.1 (3.8)
Aar-Lys	0.28 (0.20)	−0.64 (0.15)	0.31 (0.09)	1.13 (0.41)	0.31 (0.17)	−8.4 (0.2)	−9.0 (0.7)	−7.0 (0.3)	−7.1 (0.3)	−10.3 (0.3)
Aar-Rin	0.25 (0.06)	−0.02 (0.06)	0.10 (0.06)	0.61 (0.13)	0.33 (0.12)	−1.9 (3.4)	−5.6 (2.2)	−10.9 (9.9)	1.7 (1.3)	2.4 (2)
Aar-Thu	0.42 (0.13)	0.19 (0.10)	0.26 (0.09)	0.67 (0.24)	0.56 (0.18)	−7.0 (3.4)	4.1 (12)	−10.8 (10.1)	−7.7 (1.5)	−8.0 (1.7)
Arv-Gva	0.28 (0.03)	0.26 (0.08)	0.23 (0.10)	0.28 (0.07)	0.31 (0.06)	−6.1 (4.6)	11.3 (12)	−10.5 (8.4)	−3.7 (3.2)	−18.7 (5.7)
Bir-Muc	0.15 (0.15)	−0.18 (0.13)	0.08 (0.12)	0.47 (0.19)	0.20 (0.10)	−16.9 (3.9)	4.0 (7.7)	−25.7 (4.3)	−6.1 (5.3)	−43.4 (6.5)
Bro-Pay	0.36 (0.13)	0.18 (0.16)	0.33 (0.11)	0.59 (0.20)	0.35 (0.11)	−16.9 (4.9)	6.6 (8.4)	−27.5 (3.7)	−18.4 (8.6)	−31.3 (9.4)
Chr-Kra	0.28 (0.09)	0.13 (0.28)	0.15 (0.05)	0.77 (0.16)	0.13 (0.03)	−8.3 (4.8)	11.1 (3.5)	−15.8 (4.9)	−7.0 (8.7)	−19.4 (9.1)
Eaa-Buo	0.29 (0.04)	0.27 (0.05)	0.24 (0.03)	0.36 (0.08)	0.25 (0.03)	−0.9 (2.5)	3.9 (12.8)	−7.7 (10.7)	0.4 (5.3)	0.1 (4)
Emm-Emm	0.39 (0.13)	0.18 (0.08)	0.45 (0.13)	0.66 (0.19)	0.25 (0.15)	−11.9 (4.1)	4.2 (15.3)	−16.8 (14.1)	−10.5 (8.9)	−24.3 (8.9)
Eul-Win	0.33 (0.12)	0.23 (0.09)	0.30 (0.11)	0.52 (0.19)	0.24 (0.02)	−11.9 (5.4)	−4.3 (10.2)	−26.9 (10.3)	1.6 (11.2)	−36.6 (7.7)
Gla-Rhe	0.27 (0.06)	0.02 (0.09)	0.27 (0.07)	0.58 (0.11)	0.18 (0.02)	−14.7 (5)	−0.6 (6.8)	−26.0 (9.2)	−4.3 (9)	−28.4 (6.5)
Gla-Rum	0.32 (0.09)	0.02 (0.04)	0.18 (0.07)	0.66 (0.15)	0.42 (0.06)	−10.9 (5.2)	−0.1 (7.1)	−20.0 (9.9)	4.8 (11.5)	−31.9 (5.6)
Gla-Wuh	0.53 (0.14)	0.58 (0.14)	0.40 (0.06)	0.62 (0.30)	0.63 (0.14)	−6.5 (5.1)	8.3 (8.4)	−19.4 (11.5)	9.4 (12.5)	−26.4 (6.5)
Inn-Sch	0.14 (0.09)	0.07 (0.08)	0.03 (0.14)	0.30 (0.09)	0.19 (0.09)	−7.8 (3.1)	−12.0 (2.5)	−5.6 (7.3)	−6.9 (1.7)	−11.5 (11.1)
Kan-Fru	0.11 (0.1)	0.07 (0.04)	0.08 (0.07)	0.22 (0.09)	0.06 (0.13)	−5.4 (3.3)	13.3 (2.6)	−6.0 (9.7)	−9.3 (2.2)	−2.5 (0.6)
Kem-Emm	0.66 (0.12)	0.45 (0.13)	0.56 (0.12)	0.98 (0.36)	0.63 (0.07)	−13.2 (3.9)	9.6 (13)	−17.4 (12.6)	−23.9 (7.8)	−16.0 (6.7)
Kem-Ill	0.38 (0.12)	0.26 (0.10)	0.37 (0.10)	0.46 (0.24)	0.42 (0.08)	−7.2 (7.7)	6.5 (8.2)	−19.3 (15.7)	10.4 (13.7)	−33.2 (6.8)
Lan-Rog	0.58 (0.06)	0.55 (0.16)	0.55 (0.04)	0.83 (0.11)	0.40 (0.02)	−13.4 (4.6)	1.5 (7.7)	−19.5 (8.3)	−11.5 (3.8)	−25.4 (3.8)
Lim-Bad	0.37 (0.16)	0.09 (0.06)	0.23 (0.07)	0.65 (0.33)	0.49 (0.17)	−11.0 (4)	2.1 (7.4)	−18.8 (9.2)	−13.9 (6.7)	−10.7 (5.7)
Lin-Mol	0.38 (0.05)	0.24 (0.02)	0.35 (0.05)	0.51 (0.11)	0.39 (0.11)	−7.1 (4.3)	2.7 (5.4)	−15.0 (8.2)	−10.0 (5.4)	−1.9 (4.2)
Lin-Wee	0.44 (0.13)	0.13 (0.09)	0.31 (0.14)	0.91 (0.31)	0.43 (0.24)	−9.2 (4.4)	4.1 (7.5)	−16.7 (9.1)	−12.6 (5.1)	−4.8 (5.6)
Lon-Bla	0.17 (0.06)	-0.09 (0.05)	0.11 (0.10)	0.45 (0.10)	0.20 (0.01)	−6.2 (2)	−2.7 (2)	−4.4 (6.3)	−5.4 (1)	−10.7 (2.6)
Lus-Gst	0.41 (0.06)	0.14 (0.06)	0.24 (0.03)	0.76 (0.05)	0.47 (0.04)	−3.1 (2.2)	2.4 (13.1)	−6.8 (9.1)	−3.1 (1.6)	−2.0 (1.7)
Lut-Obe	0.58 (0.07)	0.54 (0.13)	0.56 (0.03)	0.77 (0.09)	0.46 (0.09)	−8.2 (8.2)	13.7 (2)	−24.4 (14.7)	−7.3 (8.5)	−5.1 (8.1)
Muo-Ing	0.14 (0.08)	0.07 (0.06)	0.11 (0.05)	0.19 (0.15)	0.13 (0.13)	−8.5 (4.5)	12.4 (15.1)	−15.2 (9.3)	−13.2 (5.4)	−3.9 (5.7)
Onz-Hei	0.41 (0.09)	0.34 (0.14)	0.35 (0.05)	0.63 (0.14)	0.32 (0.05)	−22.7 (7.4)	−10.7 (5.8)	−30.7 (8.9)	−18.8 (8.1)	−30.4 (1.7)
Osc-Kop	0.50 (0.05)	0.48 (0.15)	0.53 (0.02)	0.73 (0.08)	0.30 (0.04)	−6.4 (2.6)	5.7 (2.2)	−8.5 (1.5)	−0.6 (4.7)	−21.8 (5.1)
Rau-Mou	0.74 (0.11)	0.55 (0.12)	0.64 (0.08)	0.96 (0.13)	0.74 (0.08)	−18.7 (8.5)	3.8 (10)	−27.1 (8.9)	−3.2 (10.3)	−46.5 (6.6)
Rep-Die	0.38 (0.12)	0.26 (0.13)	0.28 (0.06)	0.60 (0.26)	0.34 (0.03)	−16.2 (5.3)	−1.4 (6.1)	−25.8 (11.9)	−6.9 (11.9)	−37.3 (6.6)
Reu-Luz	0.38 (0.11)	0.18 (0.08)	0.24 (0.06)	0.56 (0.23)	0.51 (0.14)	−7.9 (3.3)	7.8 (9.3)	−12.9 (7)	−10.5 (3.8)	−7.0 (3.4)
Reu-Mel	0.47 (0.13)	0.29 (0.10)	0.38 (0.08)	0.68 (0.26)	0.50 (0.14)	−6.9 (3.6)	8.5 (9.9)	−11.1 (7.8)	−9.9 (4.7)	−8.0 (4.3)
Reu-See	0.19 (0.06)	0.00 (0.02)	−0.02 (0.06)	0.40 (0.14)	0.31 (0.09)	−6.4 (3.4)	4.0 (7.7)	−5.3 (5.6)	−9.0 (3.8)	−7.6 (2.4)
Rhe-Die	0.46 (0.07)	0.20 (0.04)	0.29 (0.05)	0.85 (0.15)	0.46 (0.12)	−11.0 (5.4)	−1.9 (5.8)	−11.6 (7.1)	−14.6 (5.1)	−10.9 (6.8)
Rhe-Rek	0.38 (0.17)	0.12 (0.08)	0.15 (0.05)	0.76 (0.42)	0.52 (0.17)	−12.4 (4.9)	0.7 (7.7)	−17.5 (7.4)	−14.6 (7.1)	−14.3 (6.1)
Rhe-Rhe	0.51 (0.15)	0.30 (0.13)	0.39 (0.13)	0.76 (0.35)	0.56 (0.16)	−10.8 (4.1)	3.1 (9)	−17.0 (7.6)	−11.2 (4.5)	−15.5 (5.2)
Rho-Cha	0.43 (0.02)	0.43 (0.04)	0.46 (0.04)	0.29 (0.05)	0.64 (0.08)	−8.9 (3.7)	0.8 (0.3)	−17.2 (6.4)	−5.5 (4)	−15.2 (1.4)
Rho-Pds	0.32 (0.04)	0.27 (0.03)	0.30 (0.05)	0.32 (0.07)	0.35 (0.06)	−4.3 (3.3)	7.8 (1.7)	−7.8 (5.7)	−4.5 (3.5)	−9.1 (2.5)
Rho-Sio	0.13 (0.08)	0.06 (0.10)	0.09 (0.09)	0.17 (0.06)	0.16 (0.07)	−6.7 (2.9)	−5.7 (2.5)	−5.9 (7.3)	−3.9 (2.4)	−14.8 (2)
Sag-Wor	0.24 (0.08)	0.37 (0.04)	0.13 (0.08)	0.14 (0.12)	0.28 (0.10)	0.1 (11.3)	6.0 (12)	−14.6 (9.2)	18.7 (16.5)	−5.4 (6.4)
Sih-Bla	0.40 (0.19)	0.21 (0.09)	0.33 (0.07)	0.50 (0.38)	0.51 (0.19)	−9.5 (4.8)	2.2 (9.3)	−24.7 (15.7)	−6.0 (4.7)	−9.4 (4.8)
Suz-Vil	0.23 (0.06)	0.20 (0.12)	0.30 (0.05)	0.12 (0.11)	0.26 (0.05)	−12.2 (2.7)	8.8 (12.6)	−25.7 (7.9)	14.7 (2)	−45.3 (11.1)
Thu-And	0.67 (0.21)	0.45 (0.08)	0.60 (0.13)	1.00 (0.39)	0.56 (0.17)	−15.8 (5.3)	2.5 (10.2)	−30.6 (12.9)	−11.2 (10.6)	−20.2 (7.3)
Tic-Ria	0.13 (0.09)	0.10 (0.02)	−0.05 (0.01)	0.24 (0.13)	0.18 (0.19)	−7.5 (4.5)	−4.3 (4.5)	3.4 (1.9)	−8.0 (3.4)	−20.8 (12.9)
Tos-Fre	0.53 (0.18)	0.39 (0.13)	0.53 (0.15)	0.66 (0.33)	0.52 (0.14)	−13.7 (5.6)	−0.9 (9.6)	−24.1 (8.9)	−1.7 (10.9)	−28.1 (7.3)
Tos-Ram	0.32 (0.11)	0.37 (0.18)	0.27 (0.08)	0.25 (0.14)	0.42 (0.15)	−17.0 (6.2)	−0.4 (12.6)	−32.0 (12.8)	−2.5 (14.2)	−33.8 (10.4)
Wor-Itt	0.24 (0.07)	0.60 (0.13)	0.31 (0.06)	−0.03 (0.14)	0.10 (0.03)	−1.7 (4.2)	14.1 (1.5)	−10.8 (5.8)	4.7 (7)	−11.8 (6.5)

Table 3. Same as Table 2 but for period 1978–2018. Missing data result from limited length of available time series. Table from Michel et al. (2020).

Name	Water temperature trend (°C per decade)					Discharge trend (% per decade)				
	Annual	Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn
Aar-Ber	0.39 (0.02)	0.16 (0.01)	0.41 (0.01)	0.65 (0.05)	0.32 (0.04)	1.4 (0.1)	1.4 (2.7)	0.9 (0.4)	2.5 (0.5)	2.4 (0.7)
Aar-Bri	0.24 (0.01)	0.02 (0.01)	0.16 (0.00)	0.47 (0.01)	0.31 (0.02)	0.1 (0.4)	2.4 (2.1)	2.7 (0.2)	0.9 (0.4)	0.6 (0.5)
Aar-Bru	0.43 (0.03)	0.27 (0.02)	0.52 (0.01)	0.59 (0.06)	0.33 (0.03)	4.4 (0.1)	3.7 (2.6)	4.0 (0.1)	3.9 (0.9)	6.3 (1.4)
Aar-Bra	0.43 (0.02)	0.21 (0.01)	0.49 (0.02)	0.65 (0.05)	0.37 (0.03)	–	–	–	–	–
Aar-Hag	0.49 (0.03)	0.20 (0.02)	0.48 (0.02)	0.79 (0.06)	0.46 (0.05)	–	–	–	–	–
Aar-Rin	0.31 (0.01)	0.14 (0.01)	0.43 (0.02)	0.49 (0.03)	0.19 (0.03)	0.5 (0.2)	4.5 (0.6)	2.8 (0.4)	1.3 (0.3)	0.1 (0.1)
Aar-Thu	0.37 (0.03)	0.17 (0.01)	0.38 (0.01)	0.60 (0.06)	0.32 (0.05)	1.9 (0.2)	2.7 (2.9)	0.8 (0.5)	2.8 (0.5)	3.0 (0.5)
Arv-Gva	0.20 (0.01)	0.05 (0.02)	0.25 (0.03)	0.28 (0.02)	0.22 (0.02)	7.5 (0.6)	5.0 (3.1)	3.6 (1)	9.7 (0.2)	12.3 (1.3)
Bir-Muc	0.28 (0.03)	0.14 (0.02)	0.36 (0.02)	0.45 (0.04)	0.16 (0.03)	3.5 (0.5)	0.5 (2)	6.4 (1.3)	2.8 (1.1)	2.7 (2.9)
Bro-Pay	0.41 (0.03)	0.13 (0.01)	0.51 (0.01)	0.70 (0.04)	0.29 (0.03)	10.6 (0.3)	7.8 (2.3)	10.3 (0.4)	11.5 (1.8)	14.0 (2.4)
Emm-Emm	0.35 (0.03)	0.08 (0.01)	0.46 (0.01)	0.60 (0.04)	0.26 (0.04)	1.5 (0.7)	1.6 (3.7)	4.1 (0.8)	3.3 (2.6)	3.8 (2.7)
Eaa-Buo	–	–	–	–	–	1.5 (0.2)	3.9 (3)	2.6 (0.9)	2.9 (1)	2.0 (0.6)
Gla-Rhe	0.36 (0.01)	0.19 (0.01)	0.48 (0.01)	0.50 (0.02)	0.24 (0.01)	5.6 (0.9)	7.1 (1.8)	5.8 (1.1)	2.5 (2.1)	6.4 (2.1)
Inn-Sch	0.12 (0.01)	0.04 (0.01)	0.07 (0.02)	0.27 (0.01)	0.12 (0.02)	–	–	–	–	–
Kem-Emm	0.42 (0.04)	0.20 (0.01)	0.54 (0.01)	0.63 (0.09)	0.31 (0.03)	3.7 (0.6)	3.7 (3.3)	3.6 (0.5)	3.0 (2.5)	5.6 (2)
Lim-Bad	0.42 (0.03)	0.18 (0.01)	0.49 (0.01)	0.66 (0.07)	0.33 (0.05)	1.5 (0.6)	0.0 (1.8)	0.2 (0.4)	4.0 (1.8)	1.0 (1.6)
Lin-Mol	0.24 (0.01)	0.14 (0.00)	0.28 (0.01)	0.33 (0.01)	0.19 (0.03)	2.3 (0.4)	0.9 (1.3)	0.4 (0.7)	5.8 (0.9)	1.1 (1)
Lin-Wee	0.44 (0.03)	0.20 (0.01)	0.44 (0.01)	0.78 (0.06)	0.35 (0.06)	2.5 (0.3)	0.9 (1.8)	0.4 (0.5)	6.6 (1.2)	0.6 (1.4)
Lon-Bla	0.21 (0.01)	0.03 (0.02)	0.18 (0.03)	0.42 (0.02)	0.23 (0.01)	2.7 (0.4)	1.0 (0.6)	8.1 (1.2)	3.1 (0.6)	8.6 (0.6)
Lus-Gst	0.26 (0.02)	0.13 (0.01)	0.23 (0.02)	0.35 (0.03)	0.30 (0.02)	0.8 (0.2)	0.2 (3)	2.9 (0.3)	1.7 (0.5)	2.9 (0.4)
Muo-Ing	0.08 (0.02)	0.00 (0.02)	0.05 (0.02)	0.29 (0.02)	0.05 (0.04)	1.4 (0.2)	2.9 (3.8)	2.1 (0.3)	6.9 (1.3)	1.3 (1.5)
Reu-Luz	0.48 (0.02)	0.19 (0.01)	0.49 (0.01)	0.81 (0.04)	0.43 (0.04)	1.1 (0.3)	1.4 (2.4)	2.0 (0.2)	4.1 (1)	0.2 (1)
Reu-Mel	0.43 (0.03)	0.23 (0.01)	0.48 (0.00)	0.65 (0.06)	0.36 (0.04)	1.3 (0.3)	0.5 (2.6)	1.1 (0.1)	3.5 (1.2)	0.9 (1.2)
Reu-See	0.19 (0.01)	0.07 (0.01)	0.15 (0.01)	0.41 (0.00)	0.23 (0.02)	2.1 (0.4)	0.6 (1.9)	4.2 (0.9)	5.4 (0.7)	2.3 (0.7)
Rhe-Die	0.29 (0.02)	0.10 (0.01)	0.29 (0.01)	0.54 (0.04)	0.22 (0.04)	3.2 (0.2)	0.8 (1.3)	0.4 (0.9)	7.7 (0.9)	2.0 (1.2)
Rhe-Rek	0.45 (0.04)	0.20 (0.01)	0.49 (0.01)	0.75 (0.09)	0.37 (0.05)	2.5 (0.6)	0.7 (1.8)	0.9 (0)	5.0 (1.2)	3.0 (1.7)
Rhe-Rhe	0.45 (0.04)	0.22 (0.01)	0.50 (0.01)	0.70 (0.08)	0.36 (0.05)	3.3 (0.3)	1.7 (2.2)	2.4 (0.1)	4.6 (1.1)	4.0 (1.5)
Rho-Cha	0.44 (0.01)	0.25 (0.01)	0.52 (0.01)	0.55 (0.03)	0.44 (0.04)	6.7 (0.2)	4.9 (0.6)	6.1 (0.4)	7.1 (0.5)	8.6 (1.1)
Rho-Pds	0.24 (0.01)	0.13 (0.01)	0.31 (0.02)	0.21 (0.01)	0.29 (0.02)	2.7 (0.7)	1.2 (0.6)	1.4 (1.1)	3.6 (0.8)	5.2 (0.6)
Rho-Sio	0.13 (0.01)	0.01 (0.01)	0.17 (0.02)	0.15 (0.01)	0.18 (0.00)	3.4 (0.6)	2.1 (0.4)	0.6 (1.5)	3.5 (0.6)	7.4 (0.4)
Thu-And	0.46 (0.05)	0.27 (0.02)	0.53 (0.03)	0.64 (0.10)	0.36 (0.05)	3.9 (0.9)	3.2 (2.5)	4.8 (1.4)	3.4 (2.6)	4.1 (2.2)
Tic-Ria	0.25 (0.02)	0.19 (0.01)	0.20 (0.02)	0.39 (0.02)	0.22 (0.04)	–	–	–	–	–

The temperature trends observed are steady in time, contrary to the conclusion of previous studies in Switzerland using shorter time periods. Indeed, rather than a gradual warming, Hari et al. (2006) concluded to an abrupt warming which occurred in 1987/1988 with a ΔT of about 1 °C. For the period 1972 to 2001, previous studies concluded to no global trend before or after the abrupt 1987/1988 warming (Hari et al., 2006; FOEN, 2012). This shift was caused by the 1987/1988 shift in air temperature due to the North Atlantic Oscillation and the Atlantic Multidecadal Oscillation (Hari et al., 2006, Figura et al., 2011; Lepori et al., 2015a). Based on longer time series, we conclude that this shift is not visible in all rivers and that it is a *hiatus* on the clear and significant trend observed for water temperature. The observed warming rate almost matches the corresponding trend in observed air temperature. In some catchments, urbanization is also considered to be a driver of increasing surface water temperatures due to the increasing fraction of sealed surfaces which absorb more energy than natural surfaces and transfer this heat to surface runoff (Lepori et al., 2015a). While the mean values over all catchments for water and air temperature trends are close, the trends fro water and air temperature can significantely differ at the individual catchment scale, showing the large influence of local conditions and hydrological characteristics of a watershed on water temperature.

Warming of stream water is observed in all seasons, but is more pronounced in summer than in winter, creating a gradually increasing winter to summer stream temperature difference, which agrees with results found by Moatar and Gailhard (2006), Webb and Nobilis (2007), and Arora et al. (2016) in France, Austria, and Germany, respectively. In spring, the water temperature trend is more pronounced than the air temperature trend (consistent with Huntington et al., 2003 and Webb and Nobilis, 2007). While in general the warming of streams is rather similar to the air temperature increase, we show that discharge conditions and snow or glacier melt also play an important role, especially in summer. Indeed, there is a negative correlation between summer temperature and summer discharge. While summer periods without a remaining snow cover (and thus zero snow melt) or summers with lower precipitation lead to warmer water temperature, summers with higher precipitation or with enough snow remaining for melt at the beginning of the season show water temperature colder than usual. In this study, we also show that the catchment area does not have a strong statistical correlation with the observed water temperature trend.

In alpine streams, snow and glacier melt compensates for air temperature warming trends in a transient way, as found in North America by Isaak et al. (2016). Alpine catchments are more preserved from extreme summer temperatures than other catchments. In warm summers, such as 2003, despite an important positive anomaly in air temperature, the water temperature anomaly is considerably lower and below the observed anomaly of catchments of other regimes. This resilience is attributed to several factors impacting alpine river temperatures such as geology, topography, or permafrost (Küry et al., 2017). However, recent warm summer such as in years 2015, 2017 and 2018 suggest that this resilience tends to decrease (see Section 4.4.4 in Michel et al. (2020) for a deeper discussion). Rivers being strongly influenced by hydropeaking also exhibit a less pronounced warming than rivers of the Swiss Plateau (Figure 5). This is explained by conditions similar to alpine rivers and by the pumping of water to reservoirs at higher elevation and its consequent release at low elevation.

On the long term, a shift of the thermal and hydrological regimes of alpine catchments is evident. For example, Figure 6, obtained by averaging each day of the year (DOY) over an entire decade, shows a clear flattening of the discharge curve over the last 50 years for the Lonza River (glacier surface: 24.7 %). Instead of a peak in the second half of the summer, the last two decades show a flatter peak with a maximum at the end of June. In addition, the entire discharge distribution is shifted towards the beginning of the year, with an increase in spring and a decrease in late summer and autumn. There is a clear increase in water temperature, especially between mid-spring and mid-autumn, which is stronger in the middle of the summer, leading to a wider temperature range throughout the summer. This shift in hydrological regime and the general warming significantly changes the hysteresis curve of the water temperature versus discharge. While in the 1970s, the hysteresis was rather limited (i.e. low sensitivity to summer air temperature), it has become much wider over the last few decades as a result of a lower maximum value of the discharge cycle and a higher water temperature. This is additional evidence for alpine rivers becoming more sensitive to CC, and for potentially reacting in a strongly non-linear way in the future.

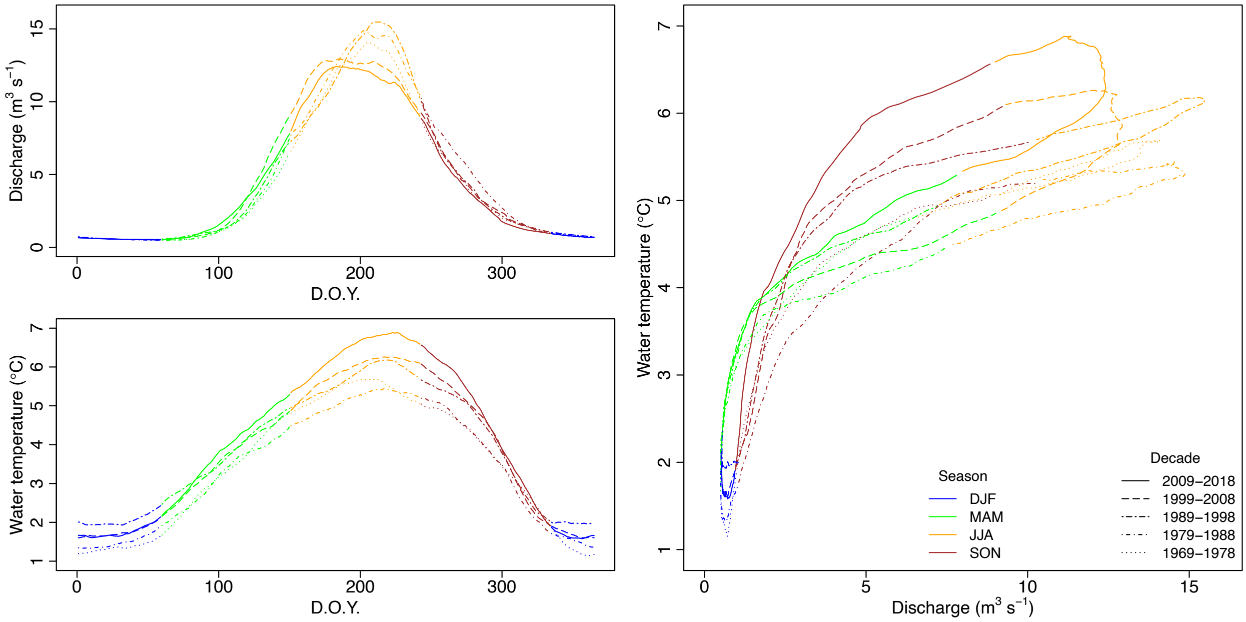


Figure 6. Left: Hydrological and thermal regimes per decade for the Lonza River in Blatten averaged for each day of the year (DOY). Line types represent decades and colours denote the seasons. Right: Decadal temperature plotted against decadal discharge (both averaged for each day of the year). Figure from Michel et al. (2020).

Table 4. Inflow and outflow water temperature trends for six different lakes; air temperature trends for stations in or close to the lake catchments. The period for trend computation is from 1979 to 2018, except for the Engelberger Aa in Buochs where the trend is computed over the 1999–2018 period due to limited data availability. Meteorological station abbreviations according to MeteoSwiss. Table from Michel et al. (2020).

Lake	Inflow station	Inflow trend (°C per decade)	Outflow station	Outflow trend (°C per decade)	Meteo station	Air temp. trend (°C per decade)
Geneva	Rhône in Porte du Scex	0.24 ± 0.01	Rhône in Chancy	0.44 ± 0.01	GVE GSB SIO	0.46 ± 0.02 0.41 ± 0.03 0.63 ± 0.02
Walensee	Linth in Mollis	0.24 ± 0.01	Linth in Weesen	0.44 ± 0.01	GLA ELM SMA	0.44 ± 0.03 0.48 ± 0.03 0.46 ± 0.03
Lucerne	Muota in Ingenbohl Reuss in Seedorf Engelberger Aa in Buochs	0.08 ± 0.01 0.19 ± 0.01 0.29 ± 0.02	Reuss in Luzern	0.48 ± 0.01	ALT ENG LUZ	0.48 ± 0.02 0.43 ± 0.03 0.48 ± 0.02
Brienz	Aare in Brienzwiler	0.24 ± 0.01	Aare in Ringgenberg	0.31 ± 0.01	MER GRH INT	0.50 ± 0.02 0.43 ± 0.03 0.52 ± 0.02
Thun	Aare in Ringgenberg	0.31 ± 0.01	Aare in Thun	0.37 ± 0.01	MER BER INT	0.50 ± 0.02 0.48 ± 0.02 0.52 ± 0.02
Biel	Aare in Hagneck	0.49 ± 0.01	Aare in Brugg	0.43 ± 0.01	BER CDF WIN	0.48 ± 0.02 0.49 ± 0.03 0.44 ± 0.02

We also show that the presence of lakes tends to increase the warming rate of the rivers flowing through them (Table 4). Indeed, for almost all the lakes under study, the water temperature trend is higher at the outlet than at the inlet. In addition, inlet water temperature trends are usually lower than surrounding air temperature trends while at the outlet both are similar. By having a long water residence time and being exposed to solar radiation, lakes act as catalysts for warming of the river flowing through the lake, and while incoming rivers might still have thermal characteristic of alpine catchments, and thus a smaller warming trend, the outflow has the same thermal characteristic as the rivers of the Swiss Plateau. The only exception is Lake Biel, where incoming water has a warming trend already similar to the surrounding air (due to its travel through Lakes Brienz and Thun upstream), so no further warming is observed due to the lake.

Take-home messages

- There has been a clear and continuous warming of the Swiss rivers in the last 40 years of +0.33 ± 0.03 °C per decade
- This warming has been more pronounced in lowlands than for alpine catchments, as glacier and snow melt is probably mitigating the warming at higher altitude
- Some shifts in timing and amplitude of discharge and in temperature regimes can already be observed in alpine catchments
- The presence of lakes along rivers increases the warming rate

2.2 Impacts of changing river temperatures

Switzerland, and in particular the alpine region, is particularly exposed to CC and its impact on hydrology. Due to the central position of the Alps in Europe and the large number of rivers fed from there, changes in the alpine region will have an impact in large parts of Europe (Viviroli et al., 2011; Huss, 2011; Finger et al., 2012; Beniston, 2012a; Fatichi et al., 2015). The literature clearly identified several socio-economic sectors, which are vulnerable: agriculture, tourism, electricity production, and water supply and quality (e.g. Hock et al., 2005; Barnett et al., 2005; Schaefli et al., 2007; Viviroli et al., 2011; Beniston, 2012a,b).

River systems are considered to be among the ecosystems most sensitive to CC (Watts et al., 2015). In Switzerland, alpine streams offer environmental heterogeneity allowing for large numbers of species and genetic diversity; changes in water availability and temperature will have an impact on the biodiversity and the ecosystem services at all levels (Hotaling et al., 2017). Water temperature is one of the most important variables for aquatic ecosystems, influencing both chemical and biological processes (Benyahya et al., 2007; Temnerud and Weyhenmeyer, 2008). For example, changes in the carbon cycle of alpine streams depending on the snow melt might turn these streams from carbon sinks to carbon sources in the future (Ulseth et al., 2018), and some ecosystems will be altered as a result of the disappearance of glacier-fed headwater streams (Hotaling et al., 2017).

Some fish species are highly sensitive to warm water, which can promote specific diseases (e.g. proliferative kidney disease, PKD) or prevent reproduction (Caissie, 2006; Carraro et al., 2016). On the other hand, higher temperatures might also be beneficial for some species, such as macro-invertebrates, enhancing biological invasion, which has been observed in the French part of the Rhône river (Paillex et al., 2017a). In general, water temperature rise is expected to lead to a shift of many species' habitat to higher elevation. However, human or natural barriers (e.g. dams, power plants) might prevent certain species to reach thermal refuges further upstream (Hari et al., 2006).

Increased water temperature will affect the usage of water for industrial cooling, such as in nuclear or other power plants (Bourqui et al., 2011). During summer 2018, the electricity production from the Mühleberg nuclear power plant, canton Bern, had to be temporarily reduced due to unusually high water temperatures of the Aare river induced by the exceptional heat wave and dry period in central and northern Europe from April through August 2018. Increase in surface water temperature is also expected to affect ground water temperature and reservoirs which are fed by river infiltration, with significant consequences on the biochemistry of these reservoirs (Section 4).

In the framework of the study described in the previous section (Michel et al., 2020), two indictors have been derived from observed stream temperatures for assessing the impact of the water temperature rise: (1) the number of days on which stream temperature reaches or exceeds the value of 25 °C, and (2) the number of consecutive days during which the hourly temperature remains above 15 °C.

The 25 °C threshold is a legal limit in Switzerland above which heat release in rivers is subject to restrictions; this is important, for example, for nuclear power plant cooling. The indicator based on hourly data and is computed as follows: if the water temperature reaches 25 °C for at least 1 hour, the day is flagged as exceeding 25 °C. Then, the number of such days per year is summed to obtain a metric for the evolution of this indicator over time.

The second indicator gives an idea of the exposure of fish to the PKD. It is computed following a simple approach inspired by the more complex model proposed in the work of Carraro et al. (2016). First, the days on which the water temperature remains above 15 °C for the whole day are computed (a 3 h moving window average is applied beforehand). Then, data are filtered to keep only series longer than 28 consecutive days. Finally, the number of days above 28 days in the remaining series are summed for each year. The results indicate the number of days in the year for which the temperature was above 15 °C for at least 28 consecutive days. As the process behind PKD is far more complex, this method does not pretend to be exact in determining the presence or absence of PKD in the rivers monitored; however, it is an indicative approach to assess the exposure evolution of the river system.

The results of the analysis for the 25 °C and 15 °C thresholds are shown in Figures 7 and 8. There is a noticeable increase in warm water events over the last decades; in particular the years of 2003 and 2018 with extremely high air temperature have a clear impact on water temperature. In the 1970s and 1980s, peaks above 25 °C were only occurring along with a significant discharge reduction. This is no longer the case in the last few decades (see e.g. years 1994, 2006, 2010, and 2012), indicating that the Swiss river system is becoming more affected by these extreme temperature events with ongoing CC. However, low discharge conditions still have an important impact on the 25 °C threshold.

For the second indicator, there is a clear increase over the past few decades on the number of days where fish might be exposed to PKD, and some rivers that were almost preserved before 1990, such as the Aare in Bern (Aar-Ber) or the Broye in Payerne (Bro-Pay) have become increasingly affected over the last two decades. During extreme years, e.g. 2003 and 2018, the increase is particularly visible.

Most of the measurement sites where warm water events are observed are located downstream of lakes and in relatively large catchments, or at low elevation on the Swiss Plateau (e.g. the Broye or the Glatt rivers). Looking at the temporal distribution during the year of days above the 15 °C threshold, they mostly occur between June and mid-October. Over time, there is a shift to earlier occurrences during the year, although the temporal conclusion of these events remains constant.

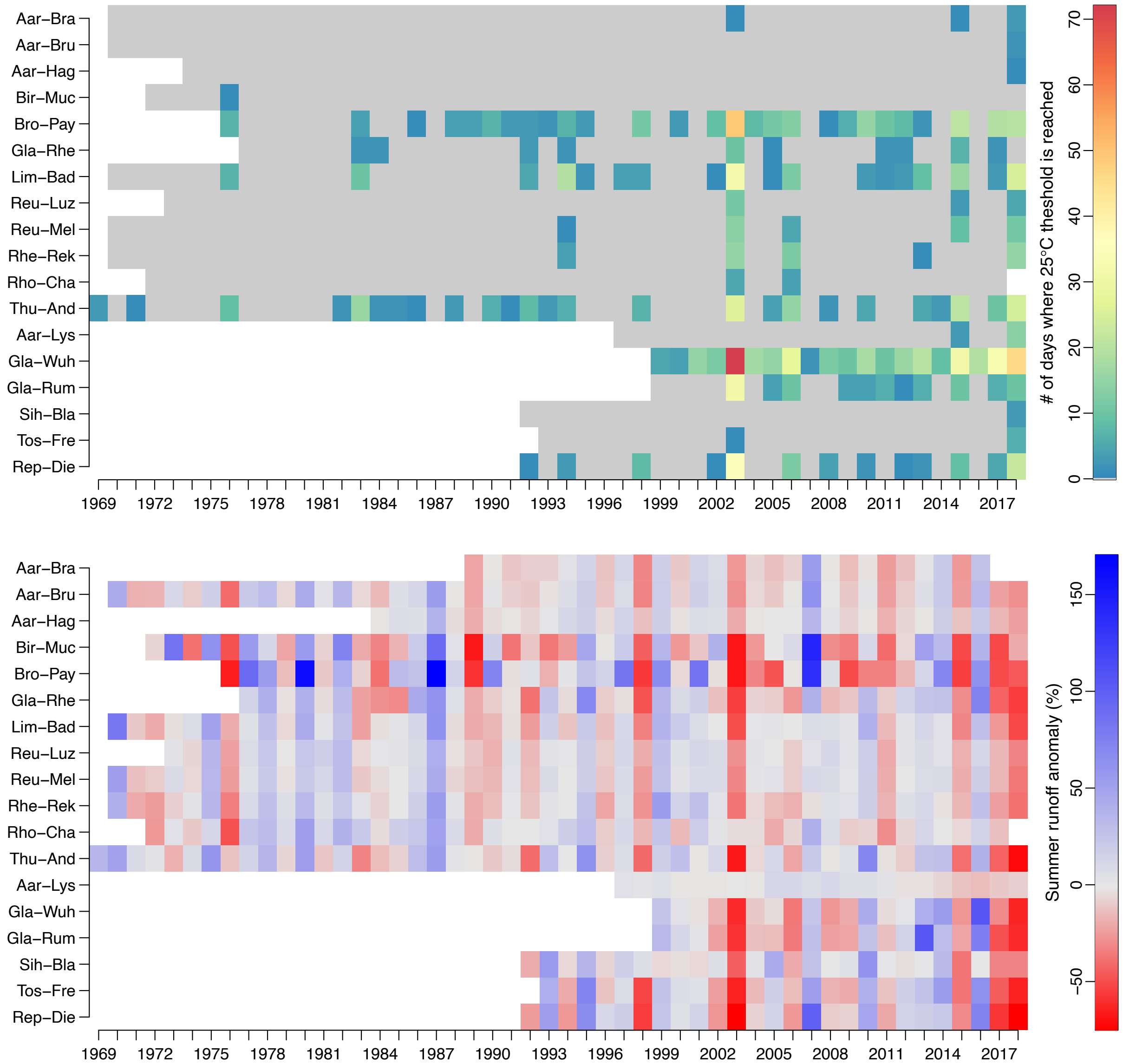


Figure 7. Top: Number of days per year when the 25 °C threshold is reached (i.e. water temperature is above 25 °C for at least 1 h during the specific day). Only catchments where the threshold is reached at least once are shown. Abbreviations of catchments names are explained in Table 1. Bottom: Summer runoff anomaly (compared to the whole periods of data availability) for the same catchment as the top panel. Figure from Michel et al. (2020).

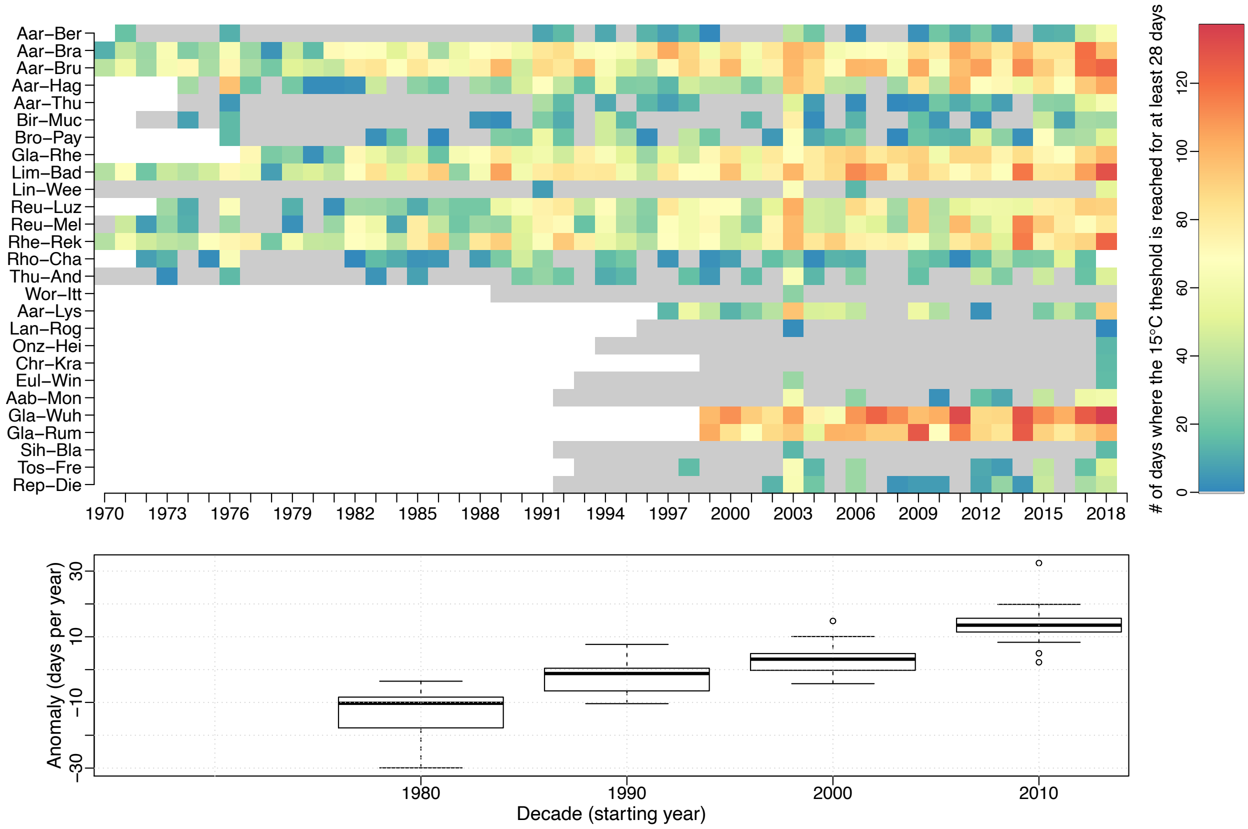


Figure 8. Top: Number of days per year when the water temperature was above 15 °C for at least 28 days (first 28 days not counted). Abbreviations of catchment names are explained in Table 1. Bottom: Anomaly in the decadal mean number of annual days when the water temperature is above 15 °C for at least 28 days (first 28 days not counted) for the 15 catchments where data are available since 1980. Anomaly with respect to the full period mean. Figure from Michel et al. (2020).

Riparian vegetation and renaturation projects are currently seen as the only effective mitigation strategy. Although such measures have already been applied, only a few recent studies have elaborated on this topic (Imholt et al., 2010, 2013; Garner et al., 2014, 2015; Kalny et al., 2017; Trimmel et al., 2018; Dugdale et al., 2018). In numerous renaturation projects, the rivers get a wider area to flow leading to shallow waters which are prone to warming (larger surface area for solar radiation absorption, larger exposure of water surface to air temperature). On the other hand, these projects usually increase the riparian vegetation, which is expected to result in a (over-) compensating cooling effect. While restoration has an influence on a large number of parameters (Paillex et al., 2017b) such as biodiversity, water quality, ecosystems, etc., the focus here is only on temperature. To date, there are only a limited number of studies which either experimentally or numerically investigated the quantitative impact of restoration measures (riparian vegetation or stream widening) on water temperature. Reduced warming of several degrees and reduced diurnal and annual variability due to riparian vegetation have been observed (Imholt et al., 2010, 2013; Garner et al., 2014; Kalny et al., 2017). The cooling effect is most pronounced in summer at daytime and for days with high net radiation gain (Garner et al., 2014, 2015). Rather than a real cooling under riparian vegetation (negative energy budget), measurements of energy fluxes suggest that the cooling effect results mainly from reduced warming (Garner et al., 2014; Dugdale et al., 2018). Models including riparian vegetation conclude that vegetation shading will be able to only partially mitigate the expected temperature rise due to CC (Trimmel et al., 2018).

Take-home messages

- River ecosystems are very sensitive to temperature change
- Fish are especially sensitive to water temperature in rivers and lakes
- Temperature change is impacting biochemical processes in streams
- River warming has an impact on water quality and water usage for industrial purposes (cooling and warming)
- Only few mitigation strategies exist to mitigate stream temperature warming (mainly vegetation shading); these are not well assessed yet

2.3 Future development of stream temperatures

In this section the main results of the study performed in the framework of this project are presented. Only few previous studies on the topic of future evolution of stream temperatures are available; these are briefly presented in the Introduction. No direct comparison with CCHydro2012 is possible since at this time only a qualitative assessment was performed while we now have quantitative results. The future development of water temperature and discharge is simulated using the physically based snow and soil model Alpine3D (Lehning et al. 2006), and the hydrological model StreamFlow (Gallice et al. 2016). The details of the method are given in Section 5.

2.3.1 Forcing Data for scenario simulations

The future evolution of discharge and stream temperature is simulated for 10 catchments in Switzerland, divided into two categories: Swiss Plateau catchments (Birs, Broye, Ergolz, Eulach, Rietholzbach and Suze) and Alpine catchments (Inn, Kander, Landwasser, Lonza), all shown in Figure 9. The land cover data used in these simulations are extracted from the European Copernicus CORINE Land Cover data set (CLC, 2006). The model is calibrated using *in situ* discharge measurements provided by the Swiss Federal Office for the Environment (FOEN), by the Canton of Bern Office of Water and Waste Management (AWA), by the Canton of Zurich Office of Waste, Water, Energy and Air (AWEL), and by Holinger AG. The model is forced using meteorological data from MeteoSwiss stations for the calibration and validation periods, and with CH2018 (2018) scenarios for future periods. A summary of meteorological and hydrological stations used for each catchment is shown in Table 5. Meteorological measurements are interpolated to grids in Alpine3D using elevation dependant interpolation algorithms. Historical glacier coverage along with their evolution under CC, used as a starting point for the simulation performed, where provided by Zekollari (2019).

The CH2018 scenarios have been released with a daily resolution, while the models used here require hourly data input. Indeed, physical processes such has snowmelt require sub-daily resolution in order to be correctly captured in models. As a consequence, a method has been developed to downscale CH2018 scenarios to hourly resolution. The method is presented in detail in Michel (2021) and all the downscaled data are available from the authors upon request. This method is based on a delta-change approach similar to the one presented by Bosshard et al. (2011) and to the approach used in CH2011 (2011).

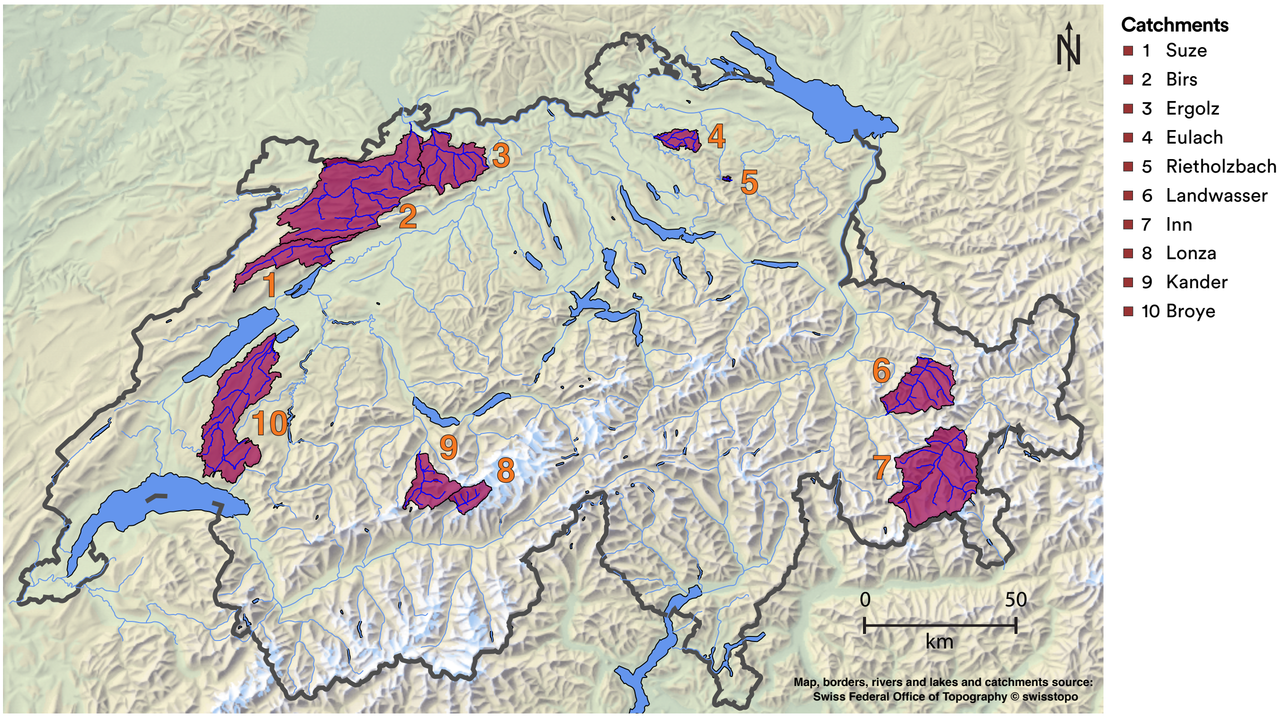


Figure 9. Catchments where the snow and river models are implemented.

Table 5. List of hydrological and meteorological stations used. The data providers for hydrological stations are indicated after the station name. For meteorological data, stations with asterisk (*) are stations where only historical measurements, but no CC scenarios, are available. All stations are MeteoSwiss stations except the RHB station, marked with a dagger (†), provided by Seneviratne et al. (2012).

River	Meteo station					Discharge station (provider)	Temperature station (provider)
Birs	BAS GRE*	BEY* MEV*	CHA RUE	COY* SAI*	DEM*	2106 Birs Munchenstein Hofmatt (FOEN)	2106 Birs Munchenstein Hofmatt (FOEN)
Broye	CDF VIT*	NEU	PAY	ROM*	ORO*	2034 Broye Payerne Caserne d'aviation (FOEN)	2034 Broye Payerne Caserne d'aviation (FOEN)
Ergolz	BAS WIT*	BUS	LAB*	MOE*	RUE	2202 Ergolz-Liestal (FOEN)	Ergolz Frenkendorf (Holinger AG)
Eulach	KLO	TAE	WIN*			ZH522 Eulach-Winterthur (AWEL)	ZH522 Eulach-Winterthur (AWEL)
Inn	BEC* SIA*	BEH*	COV	SAI*	SAM	2462 Inn S-Chanf (FOEN)	2462 Inn S-Chanf (FOEN)
Kander	ABO INT	FRU BLA*	KAS*	BOL*	KIE*	A017 Kander Frutigen (AWA)	A017 Kander Frutigen (AWA)
Landwasser	ARO*	DAV	LAT*	WFJ		2355 Landwasser Davos Frauenkirch (FOEN)	2327 Dischmabach Davos Kriegsmatte (FOEN)
Lonza	BLA VIS	EGH	JUN	ABO	INT	2269 Lonza Blatten (FOEN)	2269 Lonza Blatten (FOEN)
Rietholzbach	RHB*† ZHZEL	EBK* STG	HOE*	TAE	ZHBAM	2414 Rietholzbach Mosnang Rietholz (FOEN)	2414 Rietholzbach Mosnang Rietholz (FOEN)
Suze	CDF NEU	CHA	CHM*	COY*	MGL*	A024 Suze Pery (AWA)	A024 Suze Pery (AWA)

2.3.2 Projected changes in stream temperature

The results of the simulations for annual, winter, and summer water and air temperature, discharge and precipitation under the scenarios RCP2.6 and RCP8.5 are summarized in Tables 6 and 7 and shown in Figures 10 and 11. Under the RCP2.6 emission scenario, an annual mean warming of about 0.85 °C is expected by 2060 for both alpine and Swiss Plateau catchments. No additional significant warming is expected between 2060 and 2085. For RCP8.5, an annual mean warming of about 2 °C for Swiss Plateau catchments and of about 1.6 °C for alpine catchments is expected by the middle of the century. By the end of the century, an acceleration is expected, reaching an increase of the annual mean water temperature of about 3.2 °C for both alpine and Swiss Plateau catchments (all numbers are in comparison with the reference period 1990–2000). These annual increases correspond to 80 % of the related air temperature increase, in line with the observations over the historical period (Michel et al., 2020). On an annual basis, there are no significant trends on discharge and precipitation for the two emission scenarios and the two periods.

The seasonal behaviour shows significant differences between Swiss Plateau and alpine catchments. While Swiss Plateau catchments will experience warming both in winter and summer (with a stronger warming in summer), alpine catchments will experience almost no warming in winter (under all scenarios and periods). Indeed, even for a rise in mean winter air temperature of up to +4 °C (RCP8.5, period 2080–2090), the air temperature is close to 0 °C, which explains the low impact on water temperature (only about +1 °C). In summer, the alpine catchments will experience a stronger warming than the Swiss Plateau catchments. In addition, the warming in alpine regions is larger for water than for air temperature. This is explained by a quite abrupt decrease in discharge due to the combined effect of the decrease in precipitation and the absence of remaining snow available for melt in summer, and by the additional soil warming resulting from the absence of snow and the lower albedo. While the soil temperature increase during summer is close to the air temperature increase for Swiss Plateau catchments, it is about 1 °C above the air temperature increase in alpine catchments.

A significant modification of the discharge regime is expected for alpine catchments under RCP8.5. The annual peak is advanced from June to April-May, summer and fall discharge is drastically reduced, and winter discharge is significantly increased (Figure 12 top part). The increase in spring discharge makes alpine catchments less sensitive to the rise in air temperature during this season (Figure 12 bottom part). For Swiss Plateau catchments, an important discharge decrease is also expected over the summer, caused by a decrease in precipitation and an increase in evapotranspiration. Indeed, under the RCP8.5 emission scenario the Swiss Plateau catchments are expected to experience an increase in the mean evapotranspiration of +5 to +15 % for the period 2055–2065 and +10 to +20 % for the period 2080–2090 (corresponding values are slightly lower for alpine catchments; however, they are highly dependent on the land cover).

Table 6. Means anomalies in annual, winter and summer water and air temperature, computed between 1995 and 2060, and between 1995 and 2085 (using the periods 1990–2000, 2055–2065, and 2080–2090). Swiss Plateau catchments are: Birs, Broye, Eulach Ergolz, Rietholzbach, and Suze. Alpine catchments are: Inn, Kander, Landwasser, Lonza.

	Swiss Plateau catchments				Alpine catchments			
	RCP2.6		RCP8.5		RCP2.6		RCP8.5	
	2060	2085	2060	2085	2060	2085	2060	2085
∆ Annual water T (°C)	0.9 ± 0.2	0.9 ± 0.3	2.0 ± 0.3	3.4 ± 0.6	0.8 ± 0.2	0.8 ± 0.3	1.6 ± 0.5	3.1 ± 0.9
∆ Annual air T (°C)	1.2 ± 0.2	1.1 ± 0.4	2.6 ± 0.4	4.2 ± 0.7	1.3 ± 0.4	1.4 ± 0.6	3.0 ± 0.6	5.0 ± 0.9
∆ Summer water T (°C)	1.3 ± 0.2	1.3 ± 0.4	2.5 ± 0.6	4.7 ± 1.1	2.0 ± 0.4	1.9 ± 0.7	3.6 ± 0.91	6.3 ± 1.6
∆ Summer air T (°C)	1.5 ± 0.3	1.5 ± 0.5	3.1 ± 0.6	5.8 ± 1.6	1.7 ± 0.6	1.8 ± 0.7	3.4 ± 0.8	5.7 ± 1.4
∆ Winter water T (°C)	0.7 ± 0.3	0.7 ± 0.4	1.8 ± 0.4	3.2 ± 0.5	0.3 ± 0.1	0.6 ± 0.2	0.3 ± 0.2	1.1 ± 0.3
∆ Winter air T (°C)	0.9 ± 0.5	1.2 ± 0.6	2.5 ± 0.5	4.4 ± 0.7	0.8 ± 0.3	0.9 ± 0.7	2.4 ± 0.5	4.2 ± 0.6

Table 7. Mean anomalies in annual, winter and summer discharge and precipitation between 1995 and 2060 and between 1995 and 2080 (using the periods 1990-2000, 2055-2065, and 2080-2090). Swiss Plateau catchments are: Birs, Broye, Eulach Ergolz, Rietholzbach, and Suze. Alpine catchments are: Inn, Kander, Landwasser, Lonza.

	Swiss Plateau catchments				Alpine catchments			
	RCP2.6		RCP8.5		RCP2.6		RCP8.5	
	2060	2085	2060	2085	2060	2085	2060	2085
∆ Annual discharge %	-1.1 ± 6.6	-2.9 ± 7.9	-2.7 ± 11.4	2.0 ±10.8	-1.6 ± 7.5	-1.2 ± 6.0	-2.0 ± 2.7	-6.4 ± 14.9
∆ Annual precipitation %	1.2 ± 4.3	0.0 ± 4.4	1.5 ± 7.33	3.9 ±7.5	-0.2 ± 6.6	0.5 ± 3.8	-0.4 ± 7.7	-0.2 ± 7.8
∆ Summer discharge %	-12.7 ± 28.8	0.3 ± 12.1	-38.5 ± 34.2	-66.9 ± 32.1	15.5 ±10.3	-14.1 ± 6.3	-22.8 ± 16.0	-47.1 ±18.2
∆ Summer precipitation %	-5.6 ± 16.5	3.0 ± 6.8	-20.9 ± 19.1	-34.2 ± 20.1	11.2 ±16.4	-4.4 ± 6.1	-20.8 ± 17.4	-34.1 ±19.4
∆ Winter discharge %	-4.1 ± 9.3	-7.5 ± 16.5	2.1 ± 18.2	20.9 ±30.1	5.0 ± 9.6	5.2 ± 18.0	37.8 ± 84.7	127 ± 383
∆ Winter precipitation %	-0.6 ± 5.8	-4.3 ± 12.6	6.7 ± 12.5	23.2 ± 19.7	1.5 ± 6.7	2.8 ± 13.7	-6.9 ± 6.6	21.1 ±18.6

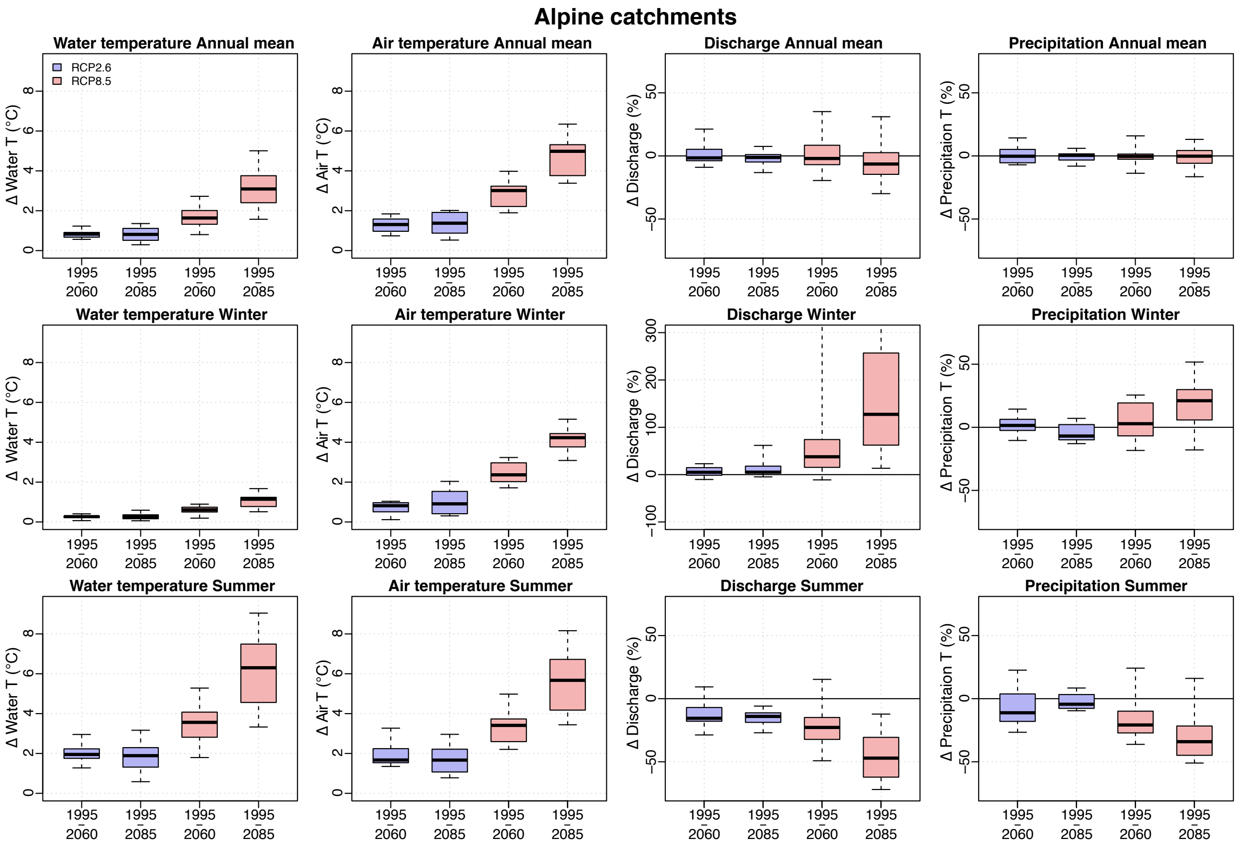


Figure 10. Means for annual, winter and summer changes in water, air temperature, precipitation and discharge for alpine catchments for RCP2.6 emission scenarios (blue) and RCP8.5 emissions scenarios (red) between 1995 and 2060 (left box for each colour) and between 1995 and 2080 (right box for each colour) computed using periods 1990–2000, 2055–2065, and 2080–2090. Alpine catchments are: Inn, Kander, Landwasser, and Lonza.

The magnitude of the warming expected in summer for both Swiss Plateau and alpine catchments (+1 °C to +2 °C for RCP2.6 and +4 °C to +8 °C for RCP8.5, both by the end of the century) will have a very significant impact and will certainly perturb the aquatic ecosystem. For example, high temperatures will accelerate the spread of diseases affecting fish. In search of colder water, they will migrate to higher altitude, but due to many built infrastructures, e.g. dams, this will not be possible everywhere. In addition, the current legal threshold of 25 °C for water temperature, above which additional heat release to streams (e.g. for industrial cooling) is limited, will be reached more often, as shown in Figure 13. Catchments already experiencing water temperature occasionally above 25 °C will see a significant increase in occurrences in the future, while catchments being preserved for now will reach this threshold in the future under the RCP8.5 emission scenario, by the end of the century.

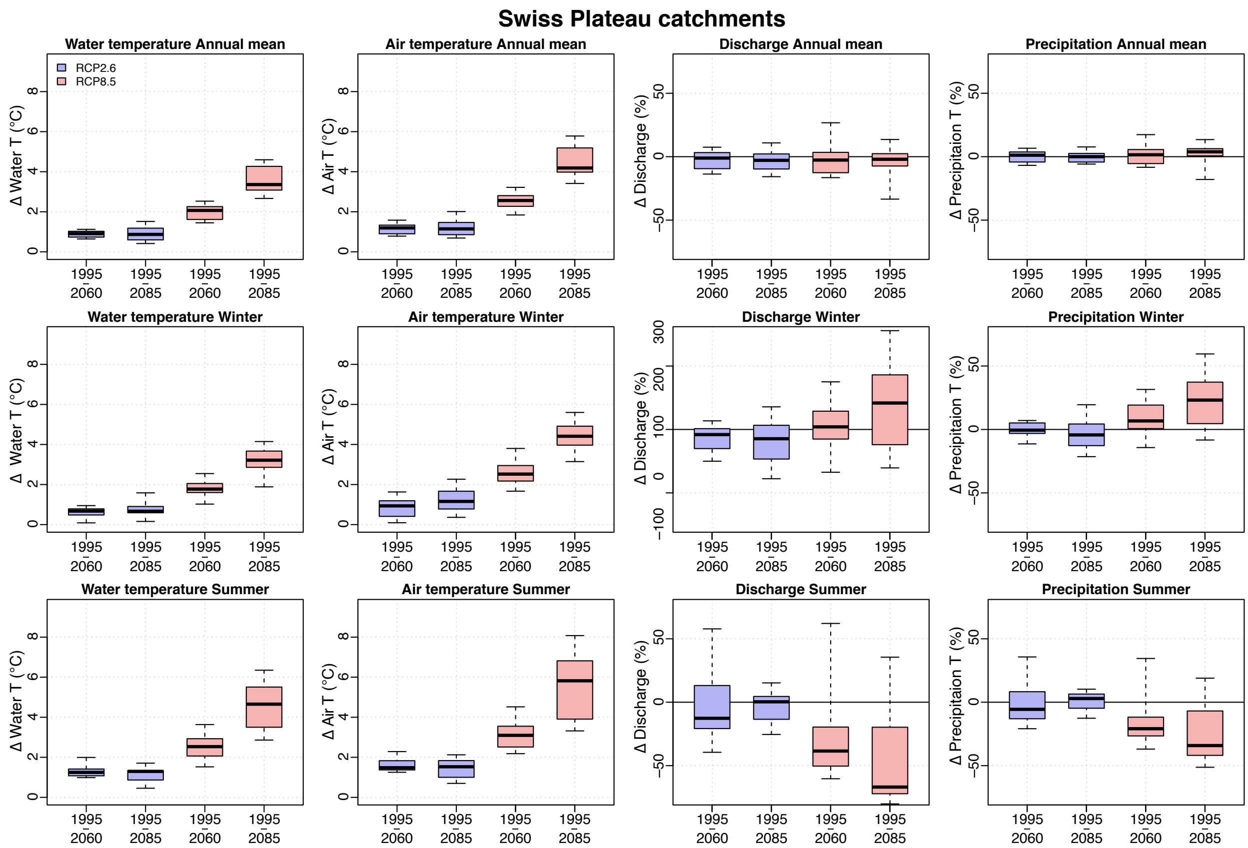


Figure 11. Means for annual, winter and summer changes in water, air temperature, precipitation and discharge for Swiss Plateau catchments for RCP2.6 emission scenarios (blue) and RCP8.5 emissions scenarios (red) between 1990 and 2060 (left box for each colour) and between 1995 and 2080 (right box for each colour) computed using periods 1990–2000, 2055–2065, and 2080–2090. Swiss Plateau catchments are: Birs, Broye, Eulach Ergolz, Rietholzbach, and Suze.

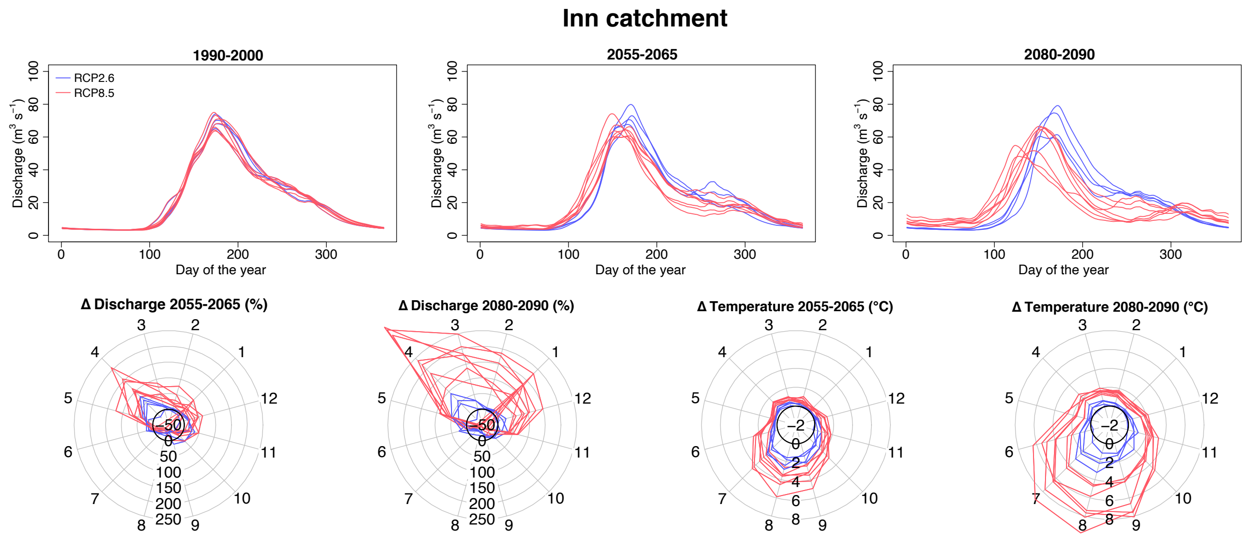


Figure 12. Top: Evolution of discharge of the River Inn in S-Chanf averaged by each day of the year for the three considered periods and for RCP2.6 (blue) and RCP 8.5 (red). Each line represents a single model chain. Bottom: Evolution of discharge and water temperature anomalies compared to the period 1990–2000, averaged by month (numbers around the polar plots indicate the months). Each line represents a single model chain.

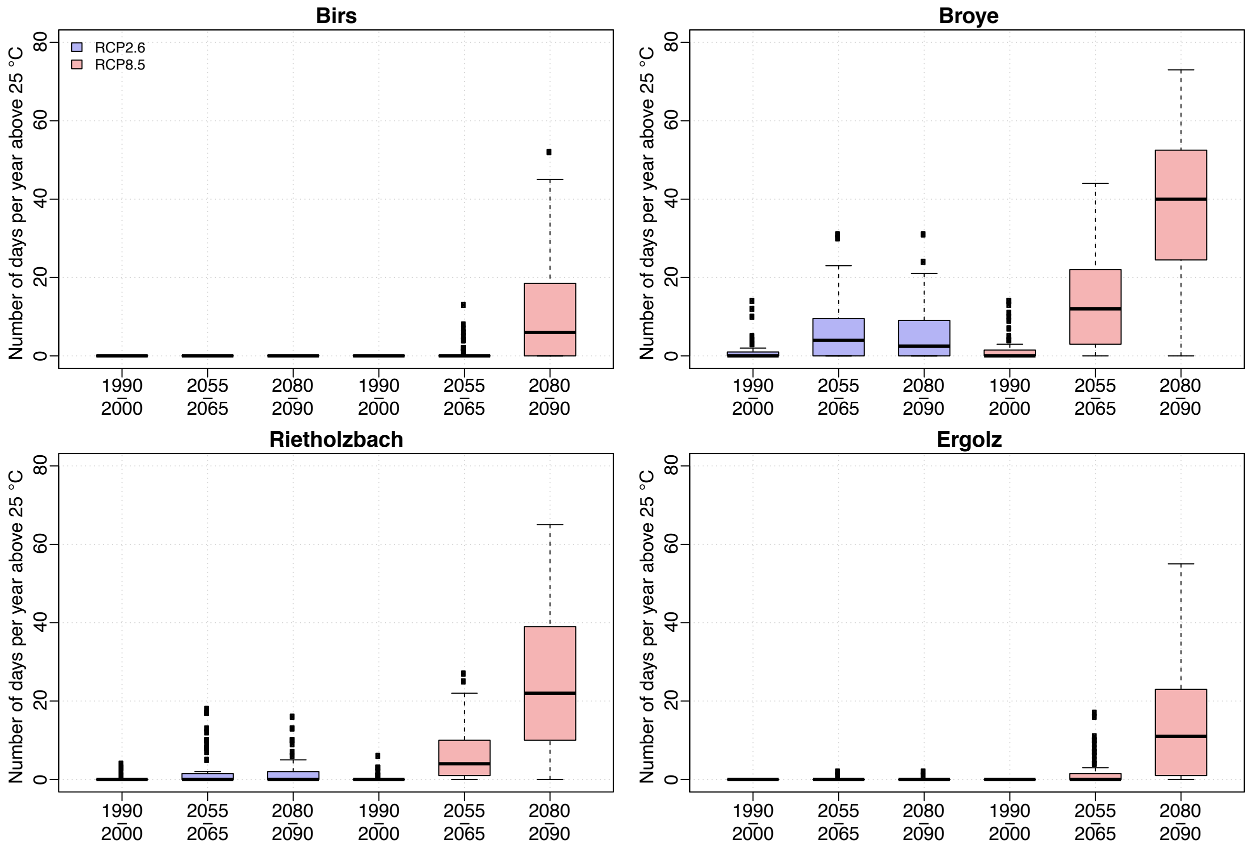


Figure 13. Number of days per year where the 25 °C threshold is reached for four catchments under the RCP2.6 emission scenario (blue) and the RCP8.5 emissions scenario (red), and for the periods 1990–2000, 2055–2065, and 2080–2090.

Take-home messages

- Significant warming is expected by mid-century for both RCP2.6 and RCP8.5
- No additional warming is expected by the end of the century for RCP2.6, while an acceleration is expected under RCP8.5
- The warming will be more important in summer, reaching +4 °C to +8 °C under RCP8.5 by the end of the century
- Alpine catchments will experience a low warming in winter but an important warming in summer (exceeding the air temperature warming). This is explained by the glacier retreat and the subsequent decrease of the soil albedo
- An important discharge regime shift is expected in alpine catchments, also contributing to the large temperature increase in summer
- The expected warming will have a significant impact and will certainly perturb the aquatic ecosystems

3 Thermal structure of lakes

3.1 Observed changes in water temperature and stratification

The vast majority of lakes worldwide show a positive trend of surface water temperatures (O'Reilly et al., 2015); for instance, central European lakes have undergone a mean summer lake surface temperature increase by 0.3 °C per decade over the period 1961-2010 (Woolway et al., 2017). Yet effects of warming vary within and between regions. This spatial heterogeneity results from both lake and watershed characteristics as well as regional variabilities in CC patterns. The heterogeneity of Swiss topography, with high mountains and wide sub-alpine plains, has resulted in a wide variety of lake systems. Observed lake temperature trends in Swiss lakes are affected by this heterogeneity and as a result show a large variability (Table 8). Swiss lakes have warmed in both surface and bottom waters with average trends of 0.40 ± 0.08 and 0.10 ± 0.05 °C per decade, respectively (95% confidence intervals of mean, Table 8). Table 8 includes both trends previously described in scientific literature, as well as trends in temperature and the duration of stratification calculated from vertical profiles of temperature provided by Swiss Cantonal agencies. For calculating the duration of stratification, we only considered years with at least nine months of measurements and lakes with at least 20 years of data. The topmost 5 m and deepest 10 m were deemed representative for the surface and bottom temperatures and used to create monthly means. The duration of the stratified period in summer was calculated after temporal linear interpolation of the temperature. Lakes were considered to be stratified if the difference between surface and bottom waters was greater than 1 °C (Foley et al., 2012). A first order linear regression analysis of stratification duration and annual mean temperature resulted in the trends given in Table 8.

3.2 Causes of observed changes

Lakes are highly dynamic systems and react differently to external forcing including a changing climate. The effects of CC are more complex than the sole manifestation on changes in air temperature. The level of warming is affected by local lake characteristics, long-term trends in atmospheric forcing, changes in frequency and distribution of extreme events, effects in the drainage area, and anthropogenic use of waters as energy sources or sinks. The complex interaction of these processes determines how lakes warm. Here, past observed warming trends and the influence of different factors are discussed.

3.2.1 Effects of external forcing

Warming of lakes is mainly driven by trends in air temperature and a corresponding increase in the incoming longwave radiation. In equilibrium with the atmosphere, the lake surface water temperature should typically increase by about 70 to 85 % of the increase in air temperature (Schmid et al., 2014; Toffolon et al., 2014). Nevertheless, in some geographical regions changes in other atmospheric variables have caused significant surface water temperature increase. Solar radiation has increased in central Europe since the 1980s due to a decrease in both cloud cover (Pfeifroth et al., 2018) and atmospheric aerosol content (Wild et al., 2007). This temporary "solar brightening" effect has contributed up to ~40 % to the recent warming of Central European lakes (Fink et al., 2014b; Schmid and Köster, 2016). Accelerated warming due to increased solar radiation was also observed for the Laurentian Great Lakes (Wahl & Peeters, 2014). Continental surface mean wind speed in the northern hemisphere has decreased since the early 1980s (about -0.1 m s^{-1} for Central Europe; Vautard et al., 2010). The reduced surface wind speed has been shown to have significantly contributed to increased surface water temperatures in lakes in the northern hemisphere (Woolway et al., 2019a) and to result in an increased stratification strength in summer and a delay of winter overturn in some US lakes (Magee & Wu, 2017). For places with wind intensity increase, the opposite occurs with deeper mixing, colder epilimnion and warmer hypolimnion (Wahl & Peeters, 2014).

Table 8. Observed temperature changes over time (trends) in surface and bottom waters as well as the duration of summer stratified period for Swiss lakes, with lower and upper 95 % confidence bounds given in brackets. Numbers (#) order lakes in ascending order according to altitude and are used to identify lakes in future projections (Section 3.4).

#	Lake	Temperature (°C dec^{-1}) Surface	Temperature (°C dec^{-1}) Bottom	Stratification duration (days dec^{-1})	Time frame	Source
2	Lower L. Lugano	0.72 (*0.43; 1.00*)	0.13 (*-0.05; 0.31*)	2.7 (*-5.5; 11.1*)	1983 – 2012	Calculated from monitoring data
		0.55			1972 - 2013	*Lepori and Roberts, 2015b*
3	Upper L. Lugano	0.51 (*0.25; 0.76*)	0.09 (*0.04; 0.14*)	8.3 (*-2.2; 18.9*)	1983 – 2012	Calculated from monitoring data
		0.4	0.1		1972 - 2013	*Lepori and Roberts, 2015b*
4	L. Geneva	0.43 (*0.31; 0.54*)	0.14 (*0.07; 0.20*)	-2.8 (*-15.1; 9.5*)	1970 - 2011	Calculated from monitoring data
		0.11			1985 - 2009*	*O'Reilly et al., 2015*
		0.22	0.17		1970 - 2000	*Lemmin and Amouroux, 2006*
5	Lower L. Constance	0.78 (*0.42; 1.13*)	0.40 (*-0.02; 0.82*)	4.2 (*-7.3; 15.8*)	1978 - 2010	Calculated from monitoring data
6	Upper L. Constance	0.38 (*0.24; 0.53*)	0.01 (*-0.04; 0.06*)	11.4 (*0.4; 22.3*)	1973 - 2014	Calculated from monitoring data
		0.53			1985 - 2009*	*O'Reilly et al., 2015*
		0.47			1977 - 2011	*Wahl and Peeters, 2014*
		0.21***	0.12		1962 - 1998	*Straile et al. 2003*
		0.46			1984 - 2011	*Fink et al. 2014b*
		0.29**			1970 - 2008	*Adrian et al., 2009*
7	Upper L. Zürich	0.44 (*0.22; 0.66*)	0.02 (*-0.18; 0.23*)	7.2 (*1.5; 12.8*)	1978 - 2005	Calculated from monitoring data
		0.41			1985 - 2009*	*O'Reilly et al., 2015*
		0.3			1972 - 2005	*North et al., 2013*
8	Lower L. Zürich	0.34 (*0.16; 0.52*)	0.08 (*0.01; 0.15*)	8.0 (*-13.3; 29.4*)	1978 - 2013	Calculated from monitoring data
		0.75			1985 - 2009*	*O'Reilly et al., 2015*
		0.41			1981 - 2013	*Schmid and Köster, 2016*
		0.24	0.13		1955 - 1993	*Livingstone, 2003*
		0.38			1970 - 2008	*Adrian et al., 2009*
		0.12****			1973 - 2014	*Woolway et al., 2019b*
9	Walensee	0.35 (*0.04; 0.65*)	0.20 (*0.04; 0.36*)	16.5 (*6.4; 26.5*)	1976 - 2000	Calculated from monitoring data
		-0.33			1985 - 2009*	*O'Reilly et al., 2015*
		0.4	0.2		1972 - 2000	*North et al., 2013*
13	L. Neuchâtel	0.25 (-0.17; 0.67)	0.01 (-0.18; 0.27)	-9.5 (-18; -1.1)	1982 - 2013	Calculated from monitoring data
18	Greifensee	0.40 (*0.12; 0.68*)	-0.08 (*-0.22; 0.06*)	14.6 (*3.7; 25.6*)	1972 - 2013	Calculated from monitoring data
		0.2			1970 - 2008	*Adrian et al., 2009*
		0.5	0.1		1972 - 2005	*North et al., 2013*
19	Pfäffikersee	0.77 (*0.48; 1.07*)	-0.08 (*-0.21; 0.03*)	3.3 (*-3.3; 12.9*)	1972 - 2013	Calculated from monitoring data

*minimum 13 years of data between 1985 and 2009
**July dataset only
***January to March
**** Minimum winter temperature

Besides the gradual change in long term atmospheric forcing fluxes, frequency and distribution of extreme events have also changed (Pachauri et al., 2015). In Switzerland warm extremes have increased while cold extremes decreased, additionally an increase in precipitation extremes is expected (Pachauri et al., 2015; CH2018, 2018). Jankowski et al. (2006) studied the impact of increased frequency of extreme heat events on Lake Zurich, which led to longer stratified conditions and more frequent deep anoxic conditions. Straile et al. (2012) showed that the extraordinarily mild winter of 2006/7 prevented the seasonal mixing of Lake Constance from reaching depths >60 m. Thus, climatically induced alterations of the distribution and occurrence rate of extreme events can locally be more influential than the long-term effect of gradual temperature increase (Perga et al., 2018; Kasprzak et al., 2017).

3.2.2 Effects of lake and watershed characteristics

The reaction of an individual lake's thermal structure to changing external forcing is modulated by the lake's characteristics, including: 1) bathymetry; 2) water clarity and light penetration; 3) stratification and mixing regime; 4) surrounding watershed with river temperature and supplied water volume; and 5) altitude.

Shallow lakes are regularly vertically mixed, and therefore react quickly to changes in the atmospheric forcing. Conversely, in deep lakes, the different depth layers react separately to atmospheric warming, depending on mixing and stratification processes. Usually, lake surface temperatures increase faster than deepwater temperatures during the summer stratification, and thus CC prolongs and increases the strength of stratification (Zhong et al., 2016; Wahl & Peeters, 2014; Arhonditsis et al., 2004; Peeters et al., 2002). The time scale at which surface temperatures adapt to changes in air temperature depends on the depth of the surface mixed layer. The depth of the surface mixed layer varies seasonally, and generally reaches deeper in wind exposed lakes compared to sheltered lakes (Livingstone, 1997). For example, a small wind-sheltered lake will have a shallow surface mixed layer in summer, and its surface temperatures will therefore react quickly to changes in air temperature. Conversely, in a large wind-exposed lake the surface mixed layer is much thicker and reacts only on time-scales of months. In this case, warming effects can accumulate during the build-up of the thermal stratification.

Effects of CC on deepwater temperatures depend on a lake's mixing regime. A changing climate can shift the stratification regime in shallow lakes from a polymictic to a dimictic regime, while deep lakes can shift from dimictic towards monomictic or oligomictic regimes (Kirillin, 2010; Woolway, 2019c). In dimictic lakes, which are inversely stratified or ice-covered in winter, the deepwater temperature at the time of seasonal mixing approaches 4 °C independent of climatic conditions. Deepwater temperatures are thereby annually reset as long as the lake remains dimictic. The amount of heat stored in the deepwater at the beginning of summer stratification is thus similar every year, and the maximum summer heat content only depends on the heat transfer from above. Small wind-sheltered dimictic lakes, where only little heat is exchanged between the epi- and the hypolimnion during summer stratification, therefore experience only a small or even no increase in deepwater temperatures (Winslow et al., 2015). In monomictic lakes, deepwater temperatures depend more on meteorological conditions (wind and air temperature) during the seasonal mixing. Some of these lakes may become oligomictic with increasing winter air temperatures. In oligomictic lakes, deepwater temperatures usually increase linearly between irregular mixing events, resulting in a typical sawtooth pattern, as has been observed in Lake Geneva, Lake Zürich, Lake Neuchâtel, and Lake Zug (Lepori & Roberts, 2015b; Peeters et al., 2002; Livingstone, 1997). The temperature at which deep mixing occurs will increase with increasing winter air temperature, resulting in a long-term rising trend of deepwater temperature. The bottom temperature trend is often smaller than the surface trend, leading to increase in stability and prolongation of the summer stratified period.

Water clarity determines how far downward shortwave solar radiation can reach and thus heat up the water. Increased water transparency enhances deep warming while counteracting surface warming, and the opposite occurs for decreased transparency (Rose et al., 2016). Thus, changes in transparency affect lake stratification and warming where in general transparent lakes heat slower at the surface and faster at intermediate depths (Kirillin, 2010). Water clarity depends on both terrestrial as well as planktonic suspended particles. The concentration of the former is driven by erosion in the catchment, while that of latter depends on the availability of light and nutrients and varies seasonally depending on the seasonal cycles of phyto- and zooplankton. Water clarity can also be affected by CC, e.g., through modified frequency and severity of floods/droughts or changed nutrient mobility in soils (Delpla et al., 2009).

Upstream drainage area processes can directly affect lake warming by supplying water with a different temperature. If the temperature trend of a tributary is comparably small, it can partially counteract climate related warming in a lake with short residence time <1000 days (Råman Vinnå et al., 2018). Such lakes are also more sensitive to anthropogenic thermal loads. An example is Lake Biel where temperature was increased on average by ~0.3 °C and locally by up to 3.4 °C from upstream heat input of nuclear power plant cooling water (Råman Vinnå et al., 2017, 2018). As glacier and snow cover diminish with atmospheric warming, river discharge is reduced in summer (less floods) and increased in winter with less precipitation bound in snow and ice (Milner et al., 2017; Addor et al., 2014; Birsan et al., 2005). This results in a temporal shift of deep penetrating river intrusion events in downstream lakes from summer towards winter thus affecting deepwater renewal and warming rates (Fink et al., 2016). In alpine regions, glacier retreat and permafrost melting modify the type of organic and inorganic particles entering into lakes, which, in turn, affects lake turbidity and light penetration and finally the thermal structure (Peter and Sommaruga 2017).

Altitude is a key parameter in mountainous regions, such as Switzerland. Lake temperature is primarily affected through lower air temperature at higher elevations, caused by adiabatic cooling. As a result, lake surface water temperatures decrease by about 6 °C/km with altitude (Livingstone et al., 2005, 1999). The timing of snowmelt in the surrounding catchment can affect downstream warming. If snowmelt occurs early, when lake stratification is not yet fully developed, meltwater can flow into the epilimnion, whereas it tends to penetrate deeper into the metalimnion or hypolimnion when snowmelt occurs later (Roberts et al., 2018). Snowmelt occurs earlier in a warming climate, consequently creating an epilimnion cooling effect, which can lead to a negative lake warming trend in early summer (Livingstone et al., 2005; Zhang et al., 2014). Liquid precipitation onto glaciers can furthermore counteract lake warming at high altitudes (Peter & Sommaruga, 2017). The cold winter conditions at higher altitudes favour the formation of ice on top of lakes (Livingstone et al., 2005). Ice-cover acts as a protective lid in winter, limiting the heat transfer between the atmosphere and lake water. Future freeze-up is expected to occur later and ice-breakup earlier, resulting in a substantially shorter ice period (Gebre et al., 2014). For large lakes with a sufficiently deep epilimnion, this can result in increased lake warming during spring and summer (Austin & Colman, 2007).

Take-home messages

- The surface temperature of Swiss lakes has gradually increased since the 1950s, on average by 0.4 °C per decade
- The warming rate decreased with depth within a lake, reaching on average 0.1 °C per decade at the lake bottom
- The response of lake thermal structure to atmospheric climate change is modulated by lake-specific factors such as altitude, bathymetry, water clarity, the stratification regime and changes in the surrounding watershed

3.3 Impacts of changing temperatures

Changes in the thermal structure of lakes affect lake water quality and lake ecosystems. The impacts are briefly discussed here and we refer the reader to Benateau et al. (2019) for a more general discussion of the effects of CC on lake water quality and ecology.

3.3.1 Effects of changes in lake thermal structure on water quality and lake ecology

It is important to recall that in lakes CC not only increases the lake temperature but also modifies the thermal structure. We essentially illustrate the consequences of an alteration of the thermal structure for lake ecology with a few examples below.

Deepwater oxygen content can be severely affected by climate induced warming (Schwefel et al., 2016). North et al. (2014) determined that climate caused hypoxia (<4 mg/l) and anoxia (0 mg/l) are mainly caused by; i) prolongation of the stratified period which allows more time for consuming oxygen in the deepwater, ii) reduced frequency and intensity of deepwater renewal caused by lake overturns or deep river intrusions, and iii) increased oxygen recovery time due to oxygen debt in the sediment, as well as iv) changes in the biological productivity within the lake. Even though the changes in (i) to (iv) might occur rapidly, the combined effect is usually a gradual worsening of the oxygen condition in the deepwater over time. To some extent, low oxygen concentrations can be mitigated by re-oligotrophication through reduction of nutrient loads, but internal release of phosphorus from the sediment might counteract restoration efforts (Søndergaard, 2007).

Of prime ecological concern is the available habitat zone for many species living in lakes, especially for fish species that are not tolerant to high temperatures. During summer stratification, their habitat can be vertically limited from above by high surface temperatures and from below by low oxygen concentrations (Jiang & Fang, 2016). With CC, surface waters are expected to become warmer, while deepwaters become more isolated from the surface by prolonged and stronger vertical stratification thus potentially decreasing oxygen content (Schwefel et al., 2016). As a consequence, the so-called oxythermal habitat, defined by the depth range where both temperatures are low enough and oxygen concentrations sufficient for coldwater fish is declining in many lakes (Magee et al., 2019). It is important to stress that these are species dependent effects. What is harmful to one organism may benefit other organisms. Examples are the anoxygenic phototrophic sulphur bacteria that require both low oxygen conditions and photosynthetically active radiation to grow efficiently (Danza et al., 2017; Sommer et al., 2017).

A key component determining lake ecology is the availability of nutrients and its seasonal fluctuations. Several processes that affect nutrient accessibility in lakes are likely affected by CC. During summer stratification, nutrients in the surface layer are consumed by phytoplankton. Prolonged stratification will tend to reduce nutrient availability towards the end of the stratified period. Furthermore, stronger density stratification will suppress the supply of nutrients from the hypolimnion by vertical mixing. Conversely, higher surface water temperatures will promote faster recycling of nutrients in the surface layer, and this can be further enhanced by preferential growth of smaller phytoplankton species under warm conditions (Bramburger et al., 2017; Winder et al., 2009), which are sinking slower than larger ones and thus export less nutrients from the surface layer into the deepwater (Acevedo-Trejos et al., 2018; Finkel et al., 2009). Furthermore, nutrient inputs from both the catchment and the mineralization of organic matter in the lake sediments tend to increase with increasing temperatures. Finally, in case seasonal mixing becomes incomplete, the recycling of nutrients in spring may be reduced, leading to low-nutrient conditions in spring, as has been proposed by Yankova et al. (2017) for Lake Zurich.

Different phytoplankton species or functional groups have different preferences concerning their environment. Therefore, the composition of the phytoplankton community may strongly depend on the physical and nutrient conditions in a lake. Cyanobacteria are a phytoplankton group which has attained widespread interest in both science and society in large, due to their ability to form large and often toxic blooms regularly linked to human activities. It has often been proposed that these small planktonic species will profit from CC due to; 1) more stable stratification and warmer temperatures in the surface layer limiting vertical transport of the cells and enhancing growth rates; 2) increased atmospheric CO_2 content which during summer blooms enables rapid replenishment of carbon depleted surface waters; 3) weather variability which may increase storms and floods, bringing more nutrients into downstream lakes; and 4) a changing aquatic food web which might or might not favour cyanobacteria through altered pressure from grazing organisms (Huisman et al., 2018). As a consequence, CC may require setting stricter nutrient reduction targets for cyanobacteria bloom control in affected lakes (Paerl et al., 2019). Yet during the past century many European lakes have started to recover from eutrophication, but the community composition did not necessarily return to conditions before eutrophication. Lake Zürich is such a system where harmful cyanobacteria blooms persist despite substantial reduction of phosphorus content (Posch et al., 2012). In this case prolongation of the stratified period, incomplete seasonal mixing, higher epilimnion temperature and increased nitrogen to phosphorus ratios still favour cyanobacteria blooms of *Planktothrix rubescens*.

In summary, while some general trends may be proposed, we are still far away from completely understanding the complexities of CC impacts on ecological processes in lakes, and it is therefore currently not possible to predict with high confidence how communities of phytoplankton, zooplankton and fish will develop in Swiss lakes under changing climatic conditions.

3.3.2 Implications of increased lake temperatures for lake monitoring and management

Anthropogenic lake warming trends have been monitored extensively in the past by the scientific community as well as by water management agencies. Due to a lack of in-situ data many lakes have been monitored through remote sensing (O'Reilly et al., 2015). However, this approach does not allow monitoring hypolimnion temperatures, which are also relevant for assessing CC impacts in deeper lakes. It is therefore important to develop and use monitoring strategies not only of surface conditions but also to follow the temporal development of deepwater temperature and stratification (Bouffard et al., 2019).

A promising option to gain further information on CC impacts on lakes is to combine in-situ monitoring methods with hydrodynamic models. These allow extending the spatially and temporally limited observational domain to the entire lake basin and thus understanding the spatial heterogeneity. However, models require calibration and validation towards in-situ measurements, and should thus not replace measurements in the field but rather act as a complement. Additionally, remotely sensed lake surface temperatures can be coupled with models to further improve model performance regarding the spatial heterogeneity of the thermal structure (Bouffard et al., 2018; Soulignac et al., 2018, Baracchini et al. 2020).

Once the lake models are set up, they can be used for various other purposes, such as projection of past or future CC impacts using CO_2 emission scenarios and regional or global climate circulation models as atmospheric forcing. Nowadays this is a commonly used method for testing the impact of different scenarios of e.g., modified forcing trends in atmospheric heat fluxes, light penetration or changes in the water supply from the catchment (Råman Vinnå et al., 2018; Fink et al., 2014b; Wahl & Peeters, 2014; Peeters et al., 2002). Models can also be used to assess the effectiveness of possible climate mitigation and management strategies.

Another concern is the diminishing usability of aquatic systems for cooling purposes where changes in temperature and water availability are predicted to put severe constraints (Van Vliet et al., 2012). However, the effect of and limitations on thermal usage are highly system dependent (Fink et al., 2014a; Gaudard et al., 2018) and to a limited extent, using lakes for heating purposes may even counteract climate warming (Brookes et al., 2013; Råman Vinnå et al., 2018). Potential strategies to diminish negative effects of climate in aquatic systems include; 1) heat pumps used for heating buildings, thereby removing heat from the lakes; 2) strategical operation of dams by adjusting production to selectively discharge colder water; 3) reforestation close to the shoreline to increase shading and limit incoming irradiance and to decrease vertical mixing through wind reduction; and 4) nutrient load reductions to limit harmful blooms and reduce surface warming through increased transparency (Brookes et al., 2013).

Take-home messages

- An assessment of CC impacts on lakes needs to consider not only changes in the surface temperature but the entire lake thermal structure
- Deepwater oxygen concentrations may decrease as a result of weaker deep mixing and more time available for oxygen consumption during a prolonged summer stratification
- The effects of CC may require further reductions of nutrient loads in order to reach water quality goals for nutrient and oxygen concentrations
- CC will likely result in significant changes in ecological processes and species composition in lakes
- Increased surface temperature and reduced deepwater oxygen concentrations may limit the optimal fish habitat zones
- Lake management may by supported by combining high frequency in situ observations with 1D and 3D models and remotely sensed observations

3.4 Future development of water temperatures

Here we project the development of water temperature, seasonal mixing and ice cover in Swiss lakes until the end of the 21st century. The present findings are summarized from Råman Vinnå et al. (2021), to which we refer for additional details. From the CH2018 climate scenarios we used 17 climate models under three future scenarios (RCP2.6, RCP4.5 and RCP8.5). The evaluation is based on transient numerical simulations for 29 lakes (Figure 14) with a one-dimensional, vertically resolved, hydrodynamic model. The simulated lakes cover a wide range of sizes, depths and water quality and are located at altitudes between 200 and 1800 m a.s.l. We quantify lake warming under all three emission scenarios at the end of the century, and in some cases complete changes of mixing regimes. We present the results by comparing the reference period (1982–2010) to the end of the century (2071–2099), yet the entire model study encompasses ~120 years (1982-2099). For clarity reasons, only the median results from model runs are provided.

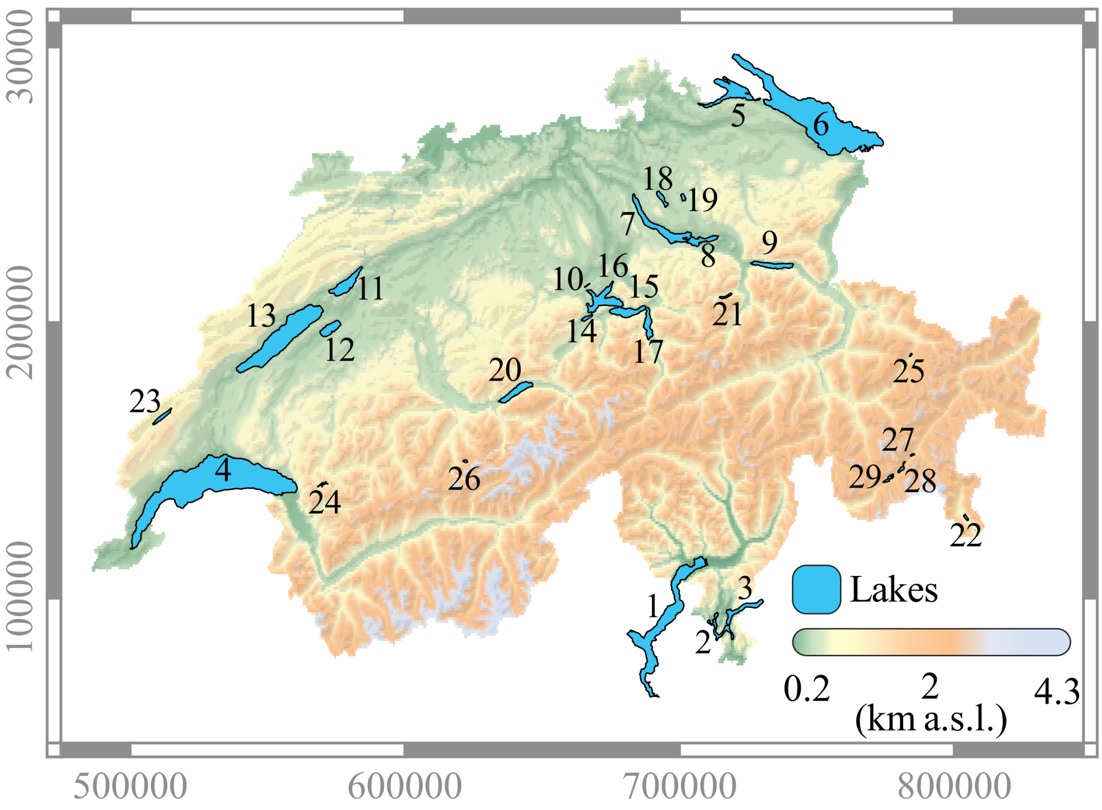


Figure 14. Topographic map of Switzerland showing lakes (numbered according to increasing altitude) for which numerical climate change simulations were run in the present study (Swiss LV03 coordinate system, topographical map from www.gadm.org version 2.8, lake outlines from www.diva-gis.org).

Table 9. Properties of the lakes included in the present study with lakes ranked in ascending order according to altitude (first column) and volume (second column). The dominant mixing regimes, defined as the regime occurring in the majority of simulated years, are given for the reference (1982–2010) and future (2071–2099) periods. Orange text indicates a stratification regime shift from 1982-2010 to 2071-2099. Multiple regimes indicate different regimes for individual RCPs. Meteorological stations used for RCM downscaling are listed in the rightmost column.

# Rank		Lake	Area	Altitude	Volume	Mixing regime		Trophic	Station
Altitude	Volume		(km²)	(m a.s.l.)	(km³)	1982-2010	2071-2099	State	
1	27	L. Maggiore	212.51	193	37	Monomictic	Monomictic	Oligotrophic	OTL
2	18	Lower L. Lugano	20.00	271	1.14	Monomictic	Monomictic	Eutrophic	LUG
3	24	Upper L. Lugano	27.30	271	4.69	Monomictic	Monomictic	Eutrophic	LUG
4	29	L. Geneva	582.21	372	89	Monomictic	Monomictic	Mesotrophic	PUY
5	16	Lower L. Constance	26.59	395	0.8	Monomictic	Monomictic	Mesotrophic	GUT
6	28	Upper L. Constance	481.72	395	47.6	Monomictic	Monomictic	Mesotrophic	GUT
7	21	Lower L. Zürich	66.60	406	3.36	Monomictic	Monomictic	Mesotrophic	WAE
8	14	Upper L. Zürich	20.30	406	0.47	Monomictic	Monomictic	Mesotrophic	WAE
9	19	Walensee	24.14	419	2.5	Monomictic	Monomictic	Oligotrophic	GLA
10	1	Rotsee	0.47	419	0.0038	Monomictic	Monomictic	Eutrophic	LUZ
11	17	L. Biel	39.30	429	1.12	Monomictic	Monomictic	Eutrophic	NEU
12	15	L. Murten	23.00	429	0.55	Monomictic	Monomictic	Mesotrophic	NEU
13	26	L. Neuchâtel	217.90	429	13.77	Monomictic	Monomictic	Mesotrophic	NEU
14	8	L. Alpnach	4.76	434	0.1	Dimictic	Monomictic	Oligotrophic	LUZ
15	23	L. Lucerne, Gersauer Becken	30.27	434	4.41	Monomictic	Monomictic	Oligotrophic	ALT
16	22	L. Lucerne, Kreuztrichter	58.92	434	4.35	Monomictic	Monomictic	Oligotrophic	LUZ
17	20	L. Lucerne, Urnersee	22.00	434	3.16	Monomictic	Monomictic	Oligotrophic	ALT
18	13	Greifensee	8.45	435	0.15	Monomictic	Monomictic	Eutrophic	SMA
19	7	Pfäffikersee	3.20	537	0.059	Dimictic	Dimictic/Monomictic	Mesotrophic	SMA
20	25	L. Brienz	29.80	564	5.17	Monomictic	Monomictic	Oligotrophic	INT
21	6	Klöntalersee	3.30	848	0.056	Dimictic	Monomictic	Mesotrophic	GLA
22	9	Lago di Poschiavo	1.98	962	0.12	Monomictic	Monomictic	Oligotrophic	ROB
23	12	Lac de Joux	8.77	1004	0.145	Dimictic	Dimictic/Monomictic	Oligotrophic	CHB:FRE
24	5	Lac de l'Hongrin	1.60	1250	0.0532	Monomictic	Monomictic	Oligotrophic	CHD:MLS
25	2	L. Davos	0.59	1558	0.0156	Dimictic	Monomictic	Oligotrophic	DAV
26	4	Oeschinensee	1.16	1578	0.0402	Monomictic	Monomictic	Eutrophic	ABO
27	3	L. St. Moritz	0.78	1768	0.02	Dimictic	Dimictic	Mesotrophic	SAM
28	11	L. Silvaplana	2.71	1791	0.14	Dimictic	Dimictic/Monomictic	Oligotrophic	SIA:SAM
29	10	L. Sils	4.11	1797	0.137	Dimictic	Dimictic/Monomictic	Oligotrophic	SIA:SAM

3.4.1 Projected changes in lake thermal structure

A system dependent increasing trend for lake temperatures was found in all 29 lakes spanning a wide range of volumes, altitudes and trophic states. The intensity of the warming is primarily linked to the emission scenario with RCP8.5 leading to the largest increase in lake temperature. Surface water temperature is projected to increase by 3.3 °C at the end of the century (~0.35 °C per decade) for RCP8.5, by 1.7 °C for RCP4.5, and by 0.9 °C for RCP2.6 (Figures 15a and 16a).

Projected deep water warming is smaller compared to that of surface waters with median temperature increases of 1.6 °C (~0.18 °C per decade) for RCP8.5, of 0.93 °C for RCP4.5, and of 0.48 °C for RCP2.6 at the end of this century. For all emission scenarios we found only minor deepwater warming rates in smaller lakes (< 0.15 km^3 and < 8.5 km^2; #1 to 13 in Figure 15b; #10, 14, 18, 19, 21 to 29 in Figure 16b). This effect is in general strongest for high altitude lakes at elevations > 1000 m a.s.l. These lakes remain dimictic and thus the bottom temperature resets to 4 °C every year. This is different in monomictic lakes, where the temperature at which the lake homogenizes increases with time. This has implications for the duration of stratification in these systems as shown in the next section.

3.4.2 Projected changes in stratification

When lakes experience vertically differential warming rates, the duration of the stratified period in summer increases. In contrast, during reversely stratified winter conditions warming shortens the stratified period. Eventually if warming continues, winter stratification may completely disappear in many lakes as surface waters never cool below 4 °C.

The higher future warming in the surface waters compared to the deepwaters results in an increased duration of the stratified period in summer. This effect is largest for RCP8.5 with summer stratification at the end of the century prolonged by -2 to 73 d (median 28 d). The effect is, as expected, smallest in RCP2.6 with -28 to 33 d prolongation (median 10 d), and intermediate for RCP4.5 with -27 to 47 d prolongation (median 14 d). The variability between lakes is linked to their volume, where stratification is prolonged more in smaller lakes than in larger lakes (Figure 15c). However, the largest increase in summer stratification duration is projected for lakes located at mid to high altitudes (higher than 800 m a.s.l.; #21 to 29, Figure 16c). For dimictic lakes we find a shortening of the stratified period in winter (Figures 15d and 16d). This change is as expected largest for RCP8.5 where the duration of winter stratification decreases by 17 to 84 days at the end of the century. The projected decrease is 12 to 41 days for RCP4.5 and 6 to 23 days for RCP2.6. The change is most severe and increasing with altitude for mid to high altitude lakes (#23 to 29 Figure 16d).

At the end of the 21st century 7 out of 8 currently dimictic lakes (mixing twice annually) are projected to shift to a monomictic (mixing once) in 7 out of 8 dimictic lakes under RCP8.5 (#14, 19, 21, 23, 25, 28, 29 in Figure 16, Table 9). Again, this effect is smallest for RCP2.6 where 3 out of 8 dimictic lakes change to monomictic (#14, 21, 25 in Figure 16, Table 9), and intermediate for RCP4.5 with a change in 5 out of 8 lakes (#14, 19, 21, 23, 25 in Figure 16, Table 9). Here we consider a lake to be dimictic if it undergoes two complete mixing events per year in more than 50 % of the years (e.g. >15 years between 2071-2099 with biannual overturns) in at least half of the model runs for one RCP. High altitude lakes (higher than 1500 m a.s.l.; Figure 16d) are least sensitive to this change, while all simulated low to mid altitude dimictic lakes (400 to 1500 m a.s.l.) switch to monomictic under RCP4.5 and RCP8.5.

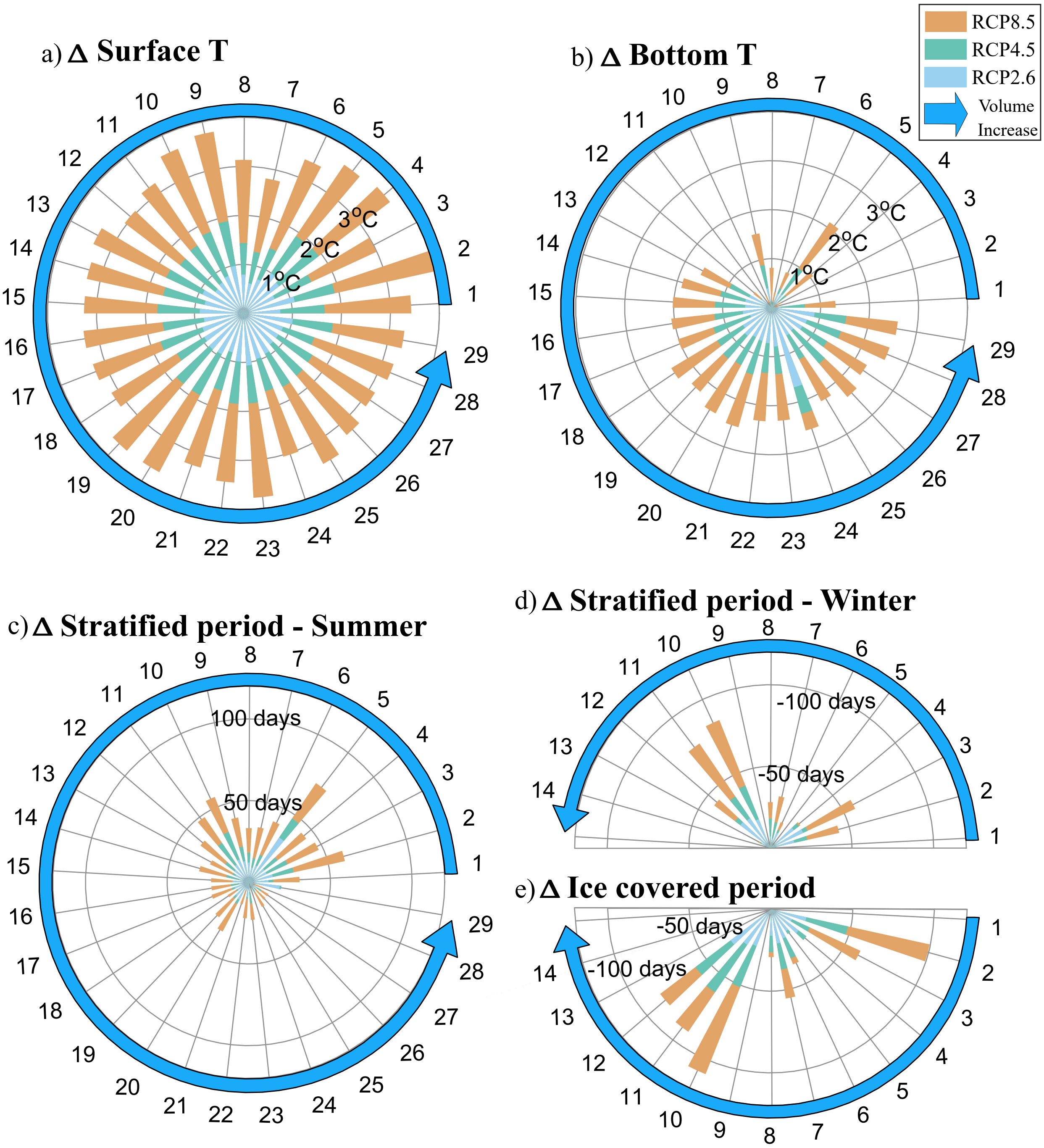


Figure 15. Projected median changes from the reference period (1982–2010) to the end of the century (2071–2099) of a) surface temperature (depth 1 m) b) deepwater temperature (1 m above bottom), c) summer stratification and d) winter stratification as well as e) ice cover duration. Lake systems are ordered with volume increasing from smallest (#1) to largest (#29) denoted by the circular arrow. Results are presented for the three emission scenarios RCP8.5 (blue), RCP4.5 (green) and RCP2.6 (orange) using seventeen or seven GCM-RCM model chains. See Table 9 for link of indices to lakes. Figure from Råman Vinnå et al. (2021).

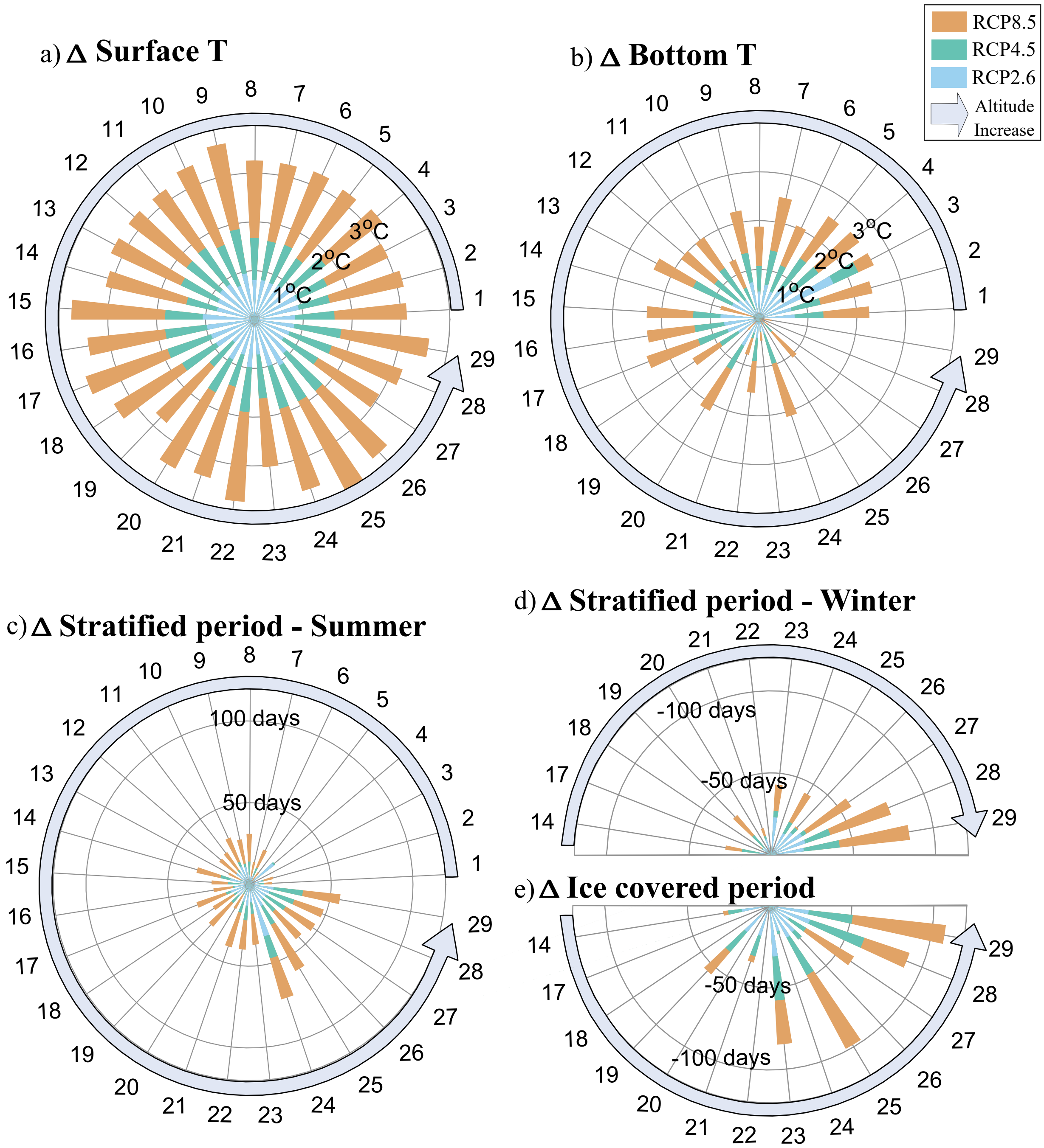


Figure 16. Projected median changes from the reference period (1982–2010) to the end of the century (2071–2099) of a) surface temperature (depth 1 m), b) deepwater temperature (1 m above bottom), c) summer stratification, d) winter stratification, and e) ice cover duration for three emission scenarios RCP8.5 (blue), RCP4.5 (green) and RCP2.6 (orange). Lakes are ordered by altitude denoted by the circular arrows from the lowest at 193 m a.s.l. (# 1) to the highest at 1797 m a.s.l. (# 29). See Table 9 for link of indices to lakes. Figure from Råman Vinnå et al. (2021).

3.4.3 Projected changes in ice-cover duration

The shortening of winter stratification (i.e. period with surface temperature below 4 °C) described in the previous section directly affects ice phenology. We find a decreasing trend for all lakes that regularly freeze over for all emission scenarios. The effect is largest for RCP8.5 with a decrease at the end of the century by 2 to 107 days, 2 to 60 days for RCP4.5 and 1 to 23 days for RCP2.6 (Figures 15e and 16e). There is a drastic decrease in the number of years at the end of the century for which ice will be present on Swiss lakes under the scenario RCP8.5 (Figure 17). The ice loss is strongest at high altitudes (Figure 16e), yet the largest effect appears at mid to low altitudes where lakes risk losing ice cover completely. Of the three lakes that completely lose ice cover by the end of the century (#14 with RCP8.5, #22 with RCP2.6 and #24 with RCP4.5), one resides at mid altitude and two reside at low altitude. It should be noted that the model projections for ice cover formation have deficiencies for some lakes under the current climate. The model simulates regular ice cover on some lakes where this never occurs (Alpnach, Biel, Lower L. Constance). Possible reasons for that are that Simstrat is calibrated towards water temperature in summer and winter but not towards ice cover thickness and the lack of sufficiently long tiem series for model calibration for some lakes.

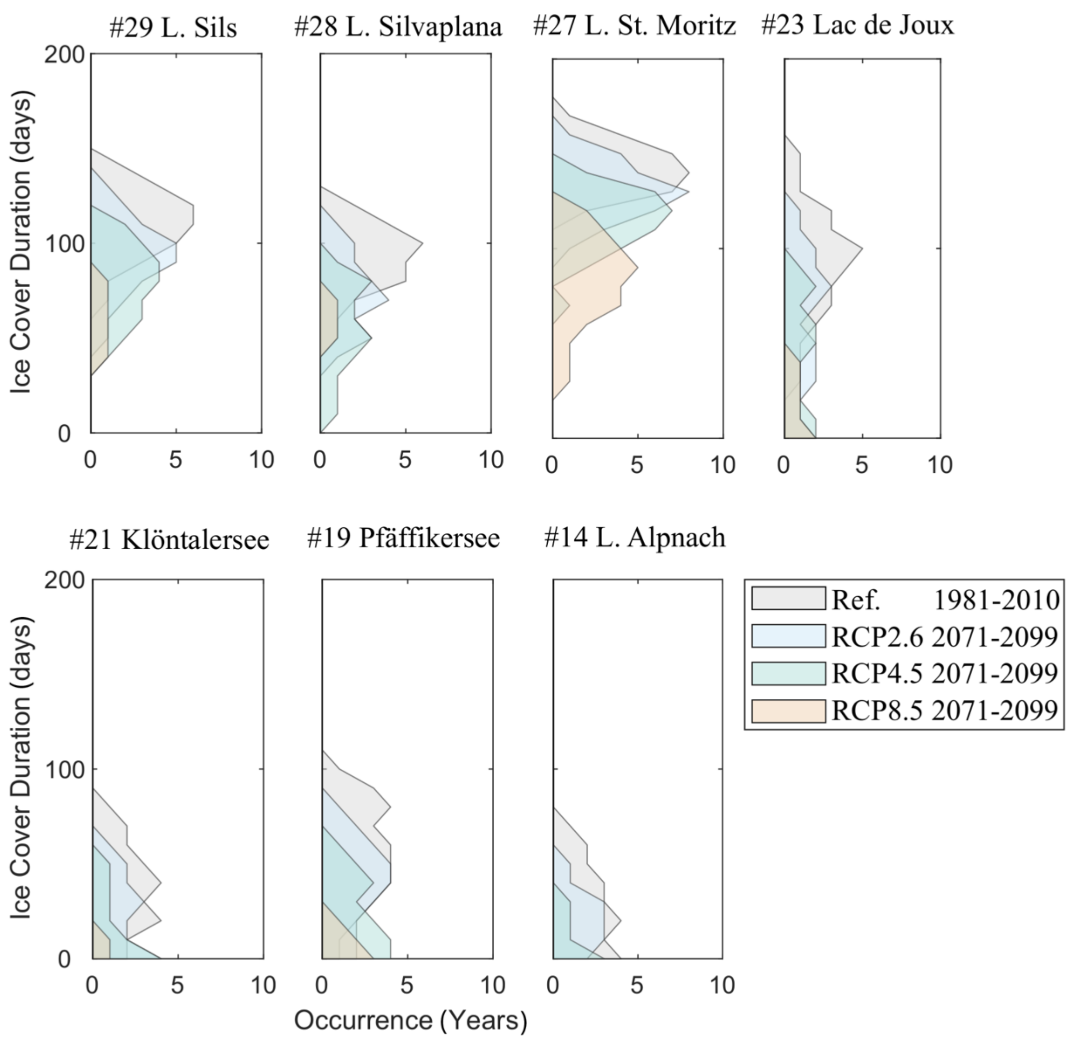


Figure 17. Projected changes of ice cover duration in lakes regularly freezing over from the reference period (1982–2010, grey) to the end of the century (1971–2099, coloured). Ice cover duration on the y-axis was binned in 10-day bins, and the x-axis indicates in how many out of 30 years the median projected ice-cover duration falls into a certain bin. Lake numbers (#) are sorted by altitude as shown in Table 9 and Figure 16.

3.4.4 Summary of findings

The detailed atmospheric forcing available in the CH2018 framework allowed for the first time to investigate in detail the effect of future climate projections on the thermal structure of Swiss lakes. Here we projected changes in the thermal structure of lakes under three scenarios (RCP2.6, RCP4.5 and RCP8.5). The warming of surface waters is least affected by local lake features and comparably homogeneous across lakes for all climate scenarios. For deepwater temperatures and stratification, the lake characteristics altitude and volume (depth) were identified as key modifiers of the reaction of individual lakes to climate forcing. These characteristics can be of similar importance as the emission scenarios for the projected changes in deepwater lake temperatures, thermal stratification, and ice cover. Deepwater warming rates are small in dimictic lakes where the deepwater temperature is reset to 4 °C every spring. This is generally the case for lakes at high altitudes or with a small volume. As a consequence of the vertically heterogenous warming rates, the duration of stratification is more sensitive to CC in small and high-altitude lakes. Conversely, lakes at low- to mid-altitude (below 1500 m a.s.l., Table 9) have an increased risk for fundamental changes in their mixing regime from dimictic (overturning twice per year) to monomictic (one overturn per year). Lakes in this altitude range that are still ice-covered in winter today might completely lose their ice cover in the future.

In summary, we identify small (<0.5 km^3) and mid- to low-altitude (<1500 m a.s.l.) lakes as especially sensitive to a future changing climate. Major changes such as shifts in stratification regimes and loss of ice cover are expected for these lakes. Lakes at higher altitudes are expected to experience large changes in the duration of summer stratification, however most of them will not pass the tipping point for complete loss of ice and maintain today's stratification regimes. As expected, the RCP8.5 scenario results in the largest CC effects on temperature, stratification and ice cover. The impact is smaller with RCP4.5 and is minimized but not eliminated with RCP2.6. Under RCP2.6 the majority of lakes in this study maintain their major present physical features such as ice cover and stratification regimes to the end of this century.

Take-home messages

- Numerical projections based on the CH2018 scenarios suggest substantial changes in lake thermal structure resulting from CC. Of notable relevance are the projected changes in ice cover duration, summer and winter stratification and mixing regimes
- The CC impacts on the thermal structure of lakes can be substantially reduced yet not eliminated for all lakes with climate protection measures as projected by RCP2.6
- Local characteristics including volume (depth) and altitude considerably modify CC related change in lakes. Water clarity had a minor impact on projected changes
- Rapid changes in the duration of summer and winter stratification are projected for high altitude lakes (~ >1500 m a.s.l), yet these lakes maintain ice cover and stratification regimes
- Small (<0.5 km^3) and mid to low altitude (~ <1500 m a.s.l.) lakes are especially sensitive to CC in the coming century, where many of these lakes may lose their ice cover or switch to a different mixing regime

4 Links between surface and groundwater temperature

Within the Hydro-CH2018 add-on module "Current status and temperature development of Swiss unconsolidated rock groundwater resources" groundwater recharge and the associated temperature imprinting for 38 Swiss porous urban and rural aquifers in the Central Plateau, the Jura region, and the Alpine region were investigated (Epting et al., 2020). This work uses the river simulations presented in Section 2.3, the main results are summarized here.

A substantial groundwater recharge component of the studied, generally highly productive, river valley aquifers is associated with infiltrating surface waters (i.e. "river-fed aquifers"). For selected climate projections, the effects of seasonal shifts of different groundwater recharge components and the sensitivity to future groundwater temperature development were determined. Generally, if runoff during summer (JJA) and autumn (SON) months decreases, it can be expected that groundwater recharge by means of infiltrating surface water will also decrease. This effect as observed could be associated with a reduction of groundwater recharge by means of comparatively "warm" surface water infiltration. In contrast, increased runoff in winter (DJF) and spring (MAM) could be associated with an increase of groundwater recharge by means of comparatively "cold" surface water infiltration. All in all, we projected these developments for the RCP8.5 scenarios, and between the periods 1995-2005 and 2080-2090, for the Rivers Birs and Ergolz in Canton Basel-Land, the River Eulach in Winterthur, and in the River Suze in Biel/Bienne. However, diverse developments resulted from the different emission scenarios. For the Rivers Birs and Ergolz in Canton Basel-Land surface runoff shifts from summer to winter under the RCP8.5 scenario, whereas no major change in mean runoff is expected for the scenarios RCP2.6. Eventually, only the "warming" effect caused by rising surface water temperatures would remain. For other rivers like the River Suze in Biel/Bienne runoff decreases in summer and increases in winter for all RCP scenarios. With single exceptions, for the River Eulach in Winterthur, and for the River Landwasser in Davos, an overall reduction of future surface water runoff is expected.

In summary, it could be shown that seasonal shifts in groundwater recharge processes could be an important factor affecting future groundwater temperatures. Moreover, the interaction with surface waters and increased groundwater recharge during high runoff periods are likely to strongly influence groundwater temperatures. Accordingly, for the "business as usual" CC scenario and for the end of the century, a shift in precipitation and river flood events from summer to winter months could be accompanied by an increase in groundwater recharge in comparatively cool seasons, which would be accompanied by a tendency to "cool down" river-fed groundwater resources. In scope of the investigations of this module for Hydro-CH2018, focus was placed on different groundwater recharge processes, including river water infiltration, and the associated temperature imprinting. However, groundwater exfiltration is also an important process for cooling stream temperatures, especially in summer, and should be studied in more detail.

Take-home messages

- The infiltration of river water is an essential component of groundwater recharge of valley aquifers ("river-fed aquifers")
- Interaction with surface waters and increased groundwater recharge during high runoff periods are likely to strongly influence groundwater temperatures
- Seasonal shifts in groundwater recharge processes could be an important factor affecting future groundwater temperatures
- A shift in precipitation and flood events from the summer to the winter months is accompanied by an increase in groundwater recharge in comparatively "cool seasons"

5 Methods

5.1 Rivers

5.1.1 Climate change scenario temporal downscaling

Here we present only a brief summary of this method developed to downscale daily meteorological time series from CH2018 scenario to hourly time series. Historical observations and CH2018 daily time series are first averaged over each single day of the year (i.e. all 1st of January together, all 2nd of January together, etc.). These time series are then smoothed with harmonic functions (using the first 7 harmonics). From these smoothed time series, the deltas between past and future periods are computed (differences for temperature and ratios for other variables which are precipitation, relative humidity, wind speed and incoming solar radiation). Finally, these deltas are applied (by addition or multiplication) to the historical hourly measured time series in order to obtain an hourly time series for the future period.

The main improvements compared to the method of Bosshard et al. (2011) used in CH2011 is the choice of optimal harmonic parameters to smooth the data and the methods to assess the quality of the obtained time series, in particular regarding the seasonal behaviour. Actually, the previous method showed a low performance in terms of capturing the seasonal changes present in the CC scenarios. The new method (Michel et al., 2021) can be shown to capture such seasonality changes more accurately. The main drawback of this method (and of all the delta-change approaches in general) is that only the amplitude of historical data is adapted according to simulated CC and not the frequency of the events in the time series. This is really important for precipitation. With this method the frequency of precipitation events is unchanged and only the amount of water for each event is adjusted, while the CH2018 dataset exhibits changes in precipitation frequency. As a consequence, the downscaled time series are not suited to study extreme events. In addition, this method enforces analysing output only at seasonal or monthly time scales since the short time variability is determined by the historical time series.

The meteorological data are downscaled to hourly data for the periods 1985–2015, 2040–2070 and 2070–2080. 17 model chains (Table 10) out of CH2018 were selected (4x RCP2.6, 6x RCP4.5 and 7x RCP8.5). Based on the information of the CH2018 technical report, these scenarios are representative of the full span of outputs of the CH2018 dataset.

Table 10. List of CH2018 scenarios used for the rivers in this study.

Scenario name	RCP2.6	RCP4.5	RCP8.5
MOHC-HADGEM2-ES_CLMCOM-CCLM4-8-17_r1i1p1 44°			x
ICHEC-EC-EARTH_HIRHAM5_r3i1p1 11°	x	x	x
ICHEC-EC-EARTH_KNMI-RACM022E_ r1i1p1 44°		x	x
MOHC-HADGEM2-ES_RACMO22E_r1i1p1 44°	x	x	x
CCCMA-CANESM2_SMHI-RCA4_r1i1p1 44°		x	x
MIROC-MIROC5_SMHI-RCA4_r1i1p1 44°	x	x	x
MPI-M-MPI-ESM-LR_SMHI-RCA4_r1i1p1 44°	x	x	x

5.1.2 Models

The future development of water temperature and discharge has been simulated using the physically based snow and soil model Alpine3D (Lehning et al. 2006), and the hydrological model StreamFlow (Gallice et al. 2016). The input data for Alpine3D are obtained from measurement stations (or temporally downscaled CH2018 scenario at these stations) and are extrapolated to the whole computation grid with an algorithm provided by the meteoIO library (Bavay et al., 2014), a complementary module of Alpine3D. Alpine3D physically simulates the snow cover, snow melt, soil temperature and vertical water transport in the soil using air temperature, precipitation, wind speed, relative humidity and incoming short- and longwave radiations as input. The core of Alpine3D is based on Snowpack, a state-of-the-art snow cover model solving the full mass and energy balances. Alpine3D outputs, in this case soil temperature and runoff at the bottom of the soil column, together with extrapolated meteorological data, are then used in StreamFlow, a semi-distributed physical hydrological model, to compute the discharge and water temperature. In this study, both models run at 500 m resolution.

StreamFlow relies on the TauDEM tool suite (Tarboton, 2014) to infer the flow path and to delimit the sub-watershed associated with each stream reach. In this project, we developed a wrapper around TauDEM to reproduce as accurately as possible the official Swiss water map provided by Swisstopo. The runoff output produced in Alpine3D is collected into each sub-watershed in StreamFlow and the residence time in the soil is determined with an approach using two linear reservoirs. The water temperature in the reservoirs is determined, depending on the catchment type, either by the energy balance approach of Comola et al. (2015) or by the approach used in the Hydrological Simulation Program–Fortran (HSPF, Bicknell et al., 1997). This second approach essentially approximates the time evolution of the water temperature in the reservoirs by smoothing and adding an offset to the time series of air temperature. The water is then routed in the river, and the evolution of water temperature is obtained by computing the energy balance for each river reach considering solar radiation, sensible and latent heat fluxes, heat exchange with the river bed, friction with the soil, and heat advection from upstream reaches. The main components of StreamFlow are shown in Figure 18.

The water residence time in the soil reservoirs and the ground heat flux need to be calibrated in StreamFlow. The calibration is achieved with a Monte Carlo approach using 10'000 random parameter sets and the corresponding model runs over the historical period. The calibration is done first for discharge, and then for temperature. The random sets are drawn in uniform distributions, with bounds corresponding to standard values available in the literature (see Gallice et al. (2016)). The performance is assessed based on daily values using for discharge the Kling-Gupta efficiency (KGE) coefficient (Gupta et al. 2009) and for water temperature the root mean square error (RMSE) compared to measurements. Some time series of meteorological stations are only available over historical time periods but not for future scenarios, since these stations are absent in the CH2018 data set, or because available historical time series are too short for the downscaling method to be applied. The model is thus calibrated for each catchment with the maximum number of stations available over the calibration and validation periods for that catchment, and is validated two times: once with the same number of stations, and once only with stations where CC scenarios are available. Note that some calibration and validation periods are rather short due to lack of measured discharge or temperature over longer time periods.

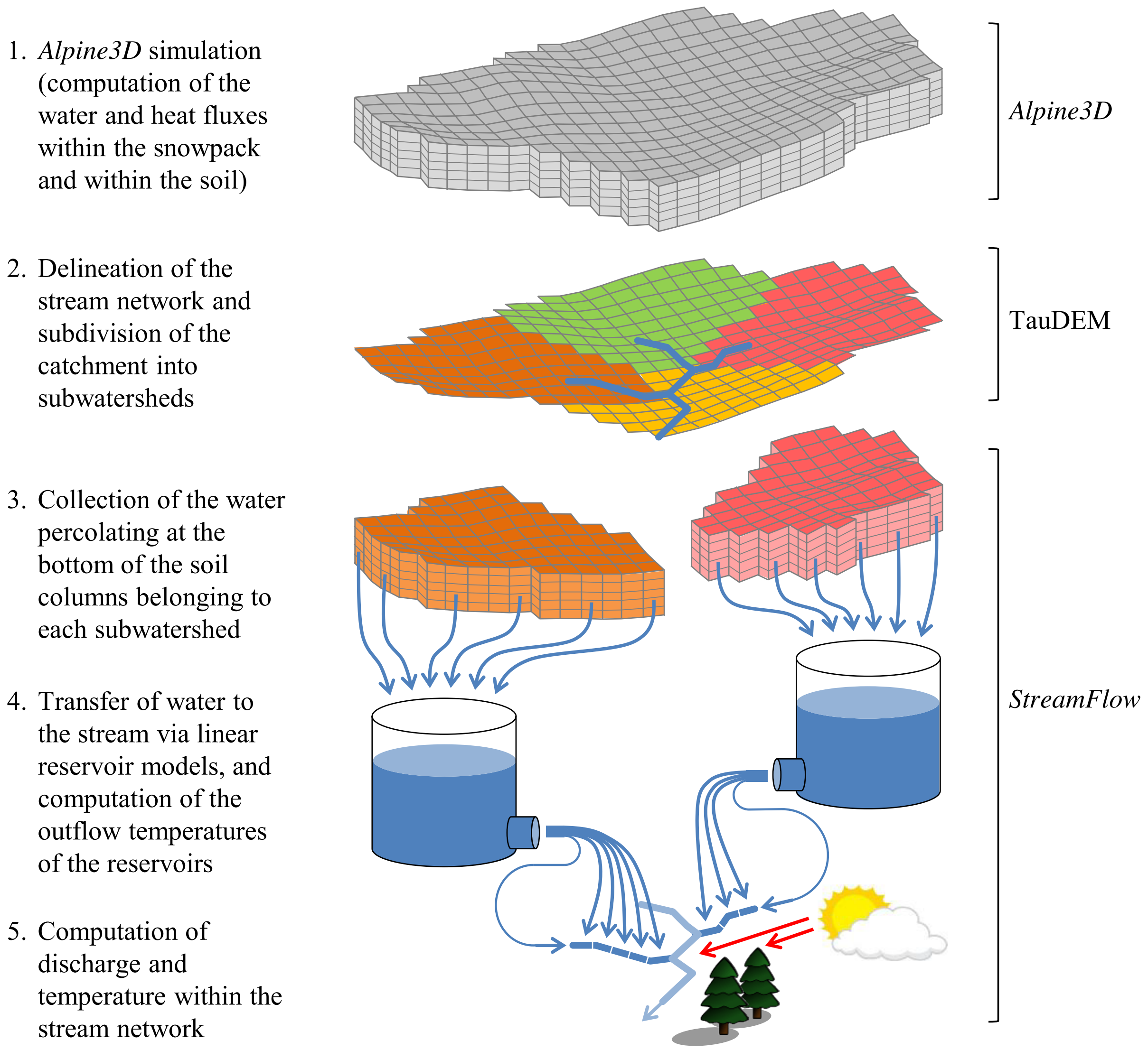


Figure 18. Schematic representation of the work flow in StreamFlow model. The first two steps are not performed in StreamFlow itself but in Alpine3D and with the help of TauDEM, respectively. Figure from Gallice et al. (2016).

Table 11 shows the resulting metrics of the model calibration. For most catchments, the Kling-Gupta efficiency KGE coefficient (Gupta et al. 2009) used to assess discharge performance is above 0.85, which is good. Results are a bit less good for the Ergolz, Broye, Landwasser and Rietholzbach, but still in an acceptable range. Regarding water temperature the mean square error MSE computed on daily values is between 0.7 and 1.9 °C for 8 out of 10 catchments except the Rietholzbach, where it is 1.57 °C, and the Suze, where it is 1.75 °C (for validation periods using only the meteorological stations also available for future periods).

The difference between the validation with all meteorological stations and the validation with a partial meteorological station set remains small for all catchments (lower than 0.2 °C except for the Ergolz and the Kander). And in some cases, the simulations with a reduced set of meteorological stations even show better results.

The models are run for the periods 1990–2000, 2055–2065, and 2080–2090. The high amount of computational resources required for the physical models and the number of scenarios used (17, leading to 51 simulations per catchment) prevent the usage of longer time periods.

Table 11. Calibration and validation Klinge-Gupta efficiency (KGE) and Mean Square Error (MSE) score used to assess the quality of discharge and water temperature simulations. “Validation full” represents the score for the validation using all meteorological stations while “validation reduced” represents the score for the validation using only station where CC scenarios are available.

River	Calibration period	Validation period	Calibration		Validation full		Validation reduced	
			T MSE (°C)	Q KGE (-)	T MSE (°C)	Q KGE (-)	T MSE (°C)	Q KGE (-)
Birs	2012 – 2014	2015 – 2018	1.19	0.80	1.28	0.87	1.32	0.86
Broye	2012 – 2014	2015 – 2018	0.93	0.70	0.94	0.77	1.1	0.73
Ergolz	2015 – 2016	2017 – 2018	0.71	0.90	0.72	0.73	1.04	0.72
Eulach	2012 – 2014	2015 – 2018	0.72	0.90	0.69	0.90	0.70	0.89
Inn	2012 – 2014	2015 – 2018	0.76	0.93	0.96	0.92	0.96	0.88
Kander	2012 – 2014	2015 – 2018	0.71	0.82	1.20	0.91	1.20	0.92
Landwasser	2015 – 2016	2017 – 2018	1.13	0.85	0.98	0.71	1.02	0.62
Lonza	2012 – 2014	2015 – 2018	0.88	0.86	0.96	0.90	0.93	0.89
Rietholzbach	2012 – 2014	2015 – 2018	1.62	0.75	1.60	0.78	1.57	0.76
Suze	2012 – 2014	2015 – 2018	2.01	0.86	1.75	0.85	1.75	0.87

5.2 Lakes

The CH2018 climate initiative aims to provide future climate projections using the latest state of the art climate modes, so called global circulation models coupled to regional climate models (GCM-RCM). GCM-RCMs are known for being inaccurate over rough topography such as the Alps. Therefore, in CH2018 a commonly known method of quantile mapping is used for statistic downscaling and bias correction, to align model output to station and gridded observations (CH2018, 2018). The result is a for Switzerland unprecedented accurate GCM-RCM output on a local scale. Accurate modelling of thermal lake processes requires detailed knowledge of multiple heat fluxes across the air-water interface. The CH2018 initiative provides meteorological forcing that includes not only air temperature but also global radiation, wind speed, relative humidity and precipitation. This enables for detailed and trustworthy modelling studies of future thermal processes in lakes located in the alpine region of Switzerland. Here we use downscaled and bias corrected output to meteorological stations to maximize the accuracy of the quantile mapping process. We selected 29 Swiss lakes for evaluating the effect of the CH2018 climate scenarios on lake thermal structure based on the following principles:

1. Selection of lakes that includes a diversity regarding bathymetry, altitude, trophic state, mixing regimes and climate regions.
2. Presence of a nearby meteorological measurement station from which atmospheric forcing data (historical as well as future downscaled GCM-RCM) of suitable atmospheric parameters could be obtained for usage in our deterministic physical lake model.
3. Available in-situ lake measurements for calibration of the deterministic model.

Details of the resulting selection of lakes are shown in Table 12. Furthermore, we selected 17 RCP8.5, 7 RCP4.5 and 7 RCP2.6 coupled GCM-RCM model chains as climate forcing from 1981 to 2099 for this study (Figure 19). In regard to representativeness these where all treated as equal and we did not adjust for differences in resolved atmospheric physics nor correctness towards measurements.

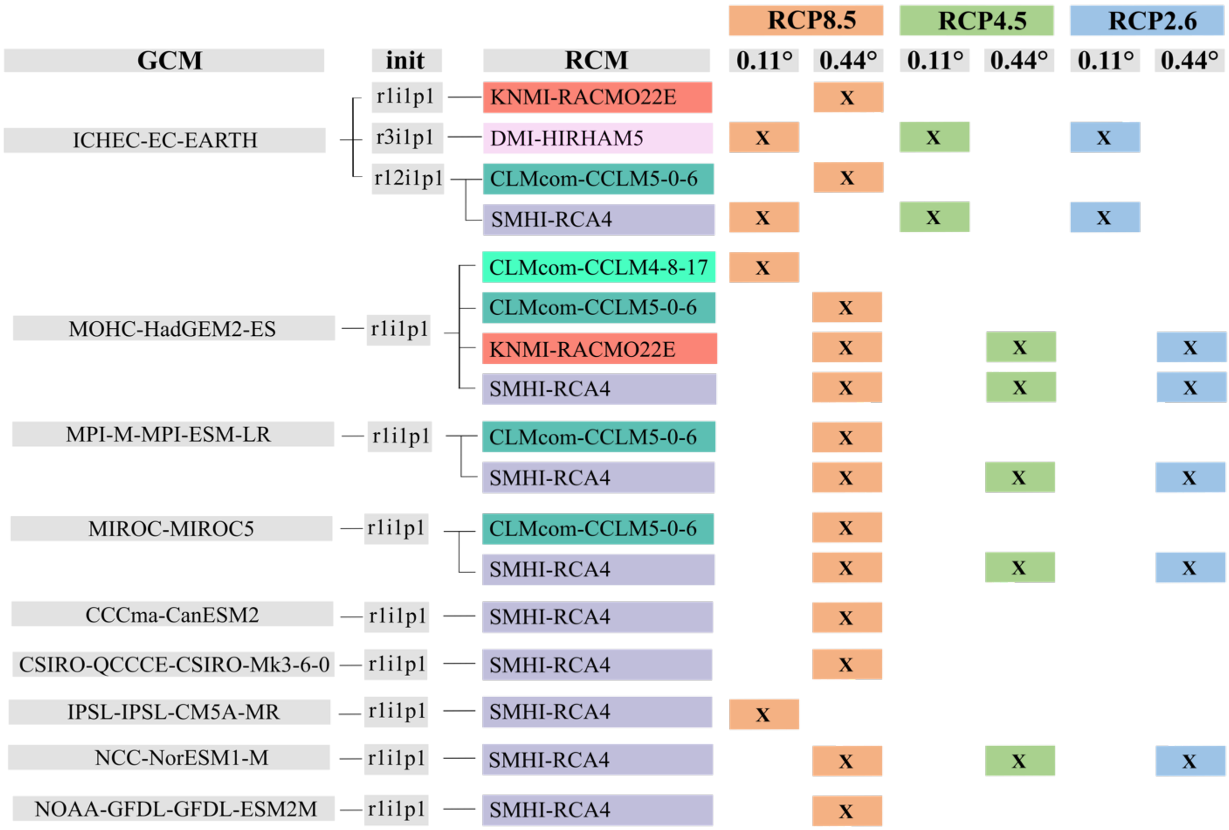


Figure 19. Selected GCM-RCM (general circulation model, regional climate model) model chains for RCP8.5, RCP4.5 and RCP2.6 emission scenarios. Figure from Råman Vinnå et al. (2021).

For investigating the impact of future climate projections on the temporal evolution of vertical temperature we use the one-dimensions Simstrat (version 2.1.2) lake model including an ice module (Gaudard et al., 2019; Goudsmit et al., 2002).

The model uses atmospheric data to estimate the heat fluxes and vertical diffusivity to derive the evolution of the thermal structure. Here we do not consider local anthropogenic influences nor the effect of the surrounding watershed. The model performance was evaluated after calibration with the PEST program (http://www.pesthomepage.org/) using both hourly and daily resolved historical forcing data (1981–2019). This yielded satisfactory results maintaining root mean square differences (RMSD) for all lakes between 0.05 and 2.74 °C (Table 12).

5.3 Source codes

The souce code for the models Alpine3D and Streamflow are freely available at:
http://models.slf.ch.

The source code for the model Simstrat is freely available at:
https://github.com/Eawag-AppliedSystemAnalysis/Simstrat.

Table 12. Lake model Simstrat parameters, constants and performance after calibration with annual forcing for each lake (Table 8) in ascending order according to altitude. Performance is displayed here as sum of squares (Sum. Sqr.), correlation coefficient (R), Number of Residuals (N. Res.) and root mean square difference (RMSD). Constants and default parameters not calibrated are given in sub-tables below.

Lake	Parameters						Best Fit Results			
	α	*α_s*	*α_w*	*f_wind*	*p_radin*	*p_albedo*	Sum. Sqr.	R	N. Res.	RMSD (°C)
L. Maggiore	0.029	-	-	1.00	0.89	-	1558	0.97	923	1.30
Lower L. Lugano	0.0092	-	-	1.44	0.89	-	5013	0.98	4724	1.03
Upper L. Lugano	-	0.043	0.002	1.44	0.92	-	5301	0.98	6659	0.89
L. Geneva	-	0.21	0.009.9	1.38	0.90	0.21	8986	0.98	10737	0.91
Lower L. Constance	0.058	-	-	0.64	0.98	0.89	12894	0.94	3761	1.85
Upper L. Constance	-	0.044	0.00063	2.04	0.94	2.00	4530	0.97	4755	0.98
Upper L. Zürich	0.017	-	-	2.03	0.97	1.81	3715	0.97	1177	1.78
Lower L. Zürich	0.07	-	-	1.33	0.98	1.11	6606	0.98	6965	0.97
Walensee	0.048	-	-	1.38	0.90	0.85	5926	0.96	4501	1.15
Rotsee	0.0053	-	-	0.92	0.97	2.00	1406	0.99	943	1.22
L. Biel	0.00092	-	-	2.42	0.98	0.48	4205	0.94	1295	1.80
L. Murten	0.0051	-	-	1.72	1.06	0.76	1658	0.96	708	1.53
L. Neuchâtel	0.0026	-	-	2.48	1.06	0.51	3113	0.98	3594	0.93
L. Alpnach	0.0034	-	-	1.00	0.86	1.46	110	0.98	82	1.16
L. Lucerne, Gersauer Becken	0.022	-	-	1.546	0.84	-	13	0.60	21	0.78
L. Lucerne, Kreuztrichter	0.46	-	-	0.80	0.90	0.22	92	0.97	127	0.85
L. Lucerne, Urnersee	0.0058	-	-	1.02	0.92	-	0.1	0.97	19	0.07
Greifensee	0.0064	-	-	1.07	0.94	1.08	3749	0.99	4872	0.88
Pfäffikersee	0.0027	-	-	0.49	0.86	0.98	8697	0.96	3749	1.52
L. Brienz	0.05	-	-	0.90	0.80	1.17	4214	0.95	3072	1.17
Klöntalersee	0.0066	-	-	1.42	0.87	1.90	142	0.94	62	1.51
Lago di Poschiavo	0.032	-	-	1.18	0.89	0.90	2903	0.93	1205	1.55
Lac de Joux	0.012	-	-	0.83	0.89	2.00	54	0.99	99	0.74
Lac de l'Hongrin	Default	-	-	Default	Default	Default	-	-	0	-
L. Davos	Default	-	-	Default	Default	Default	-	-	0	-
Oeschinensee	0.076	-	-	1.02	0.88	0.70	87	0.97	163	0.73
L. St. Moritz	0.0062	-	-	1.08	0.87	0.99	484	0.97	939	0.72
L. Silvaplana	0.005	-	-	1.75	0.95	2.00	2074	0.97	3859	0.73
L. Sils	0.018	-	-	0.97	0.96	1.27	76	0.99	750	0.32

Constants	
lat	lake dependent
p_air	lake dependent annual mean
q_nn	1.1
cd	0.002
hgeo	lake dependent
k_min	$1x10^{-9}$
Sesonal *α* shift at max(N^2)	2e-4 s^{-2}
freez temp.	0 °C
snow temp.	2 °C

Default Parameters	
α	0.00
f_wind	1.0
p_radin	1.0
p_albedo	1.0
β_sol	0.35

6 Knowledge gaps and research needs

Inland aquatic water systems are vital for prospering societies and display a highly variable reaction to CC. Detailed and individual system-based knowledge of how these water bodies react to warming are essential to enable development of mitigation and adaptation strategies. The present study is the first explicit numerical simulation that includes all relevant meteorological forcing variables and all heat fluxes between the atmosphere and the water surfaces investigating the impacts of a set of regional climate projections on the evolution of river temperature and on the thermal structure of lakes in Switzerland. It thus results in the most complete picture of the current state and the vulnerability of the Swiss river network and on the thermal structure of Swiss lakes to CC up to date. Nevertheless, knowledge gaps remain concerning the impacts of CC.

The projections of river temperature presented in this study are only performed over undisturbed catchments. Indeed, even if the inclusion of hydropower facilities and other industrial impacts is technically feasible and historical data do exist to run models, uncertainties regarding the future usage of hydropower in Switzerland, especially in the perspective of the energy transition, prevents the inclusion of such elements in models. The second important point for river temperature is the fact that the method used to temporally downscale the forcing CC scenarios does not capture correctly changes in extreme events. While no impact on the long-term water temperature trends is expected from extreme events, short time impacts and effects on water turbidity, an important variable that might affect downstream lake temperature, are expected. Also, it has to be noted that no river from the south of the Alps was simulated for CC projection, and only one river from Ticino is included in the analysis of past temperature trends. A work more focused on the impact of CC in Ticino, which can be expected to sensibly differ from the rest of the country, would be relevant.

The current and foreseen warming of Swiss rivers is expected to have a large impact on many aquatic ecosystems. Many biochemical processes will be altered; however, the exact type and range of these alterations are still largely unknown. Further work assessing the impact of stream warming on the ecosystem is thus required. Another aspect which should be covered in future investigations is the "cooling- and heating-effect" of exfiltrating groundwater into surface water, especially during low-flow periods for rural and urban areas.

At global scale, adaptation and mitigation are widely discussed. For the Swiss river network, while the figures obtained in this study allow for a gradual more accurate work on adaptation strategies, mitigation possibilities have not been investigated yet. Riparian vegetation shading is seen as the most promising mitigation strategy. However, further studies involving *in-situ* measurements and numerical modelling are required to propose effective mitigation strategies.

Regarding the thermal structure of lakes, some processes were not represented in sufficient detail in the numerical simulations of the present study. These include the effects of climatically driven modifications in the lake catchments such as the influence of changed precipitation or land use patterns on the supply of suspended particles and nutrients, or the thermal impacts of shifts in timing and amount of inflowing water from snowmelt. Coupling of the numerical models of rivers and lakes used in the present work would be of particular interest to address some of these questions. While this has been a planned component of this project, time constraints prevented its realization.

In Switzerland, but also globally, it is of particular interest to identify which types of lakes are most vulnerable to CC. Such analyses must consider CC impacts on the entire thermal structure of lakes, including surface and bottom water temperature, strength and duration of stratification, as well as frequency and intensity of deep mixing, as performed in the present study. However, these changes also have fundamental impacts on biogeochemical processes. Numerous studies have previously pointed out potential impacts of CC on lake biogeochemistry and ecological interactions under specific circumstances or for individual lakes. However, generalizing these findings for a large number of lakes and accurately considering the entire chain of processes from climate forcing to lake biogeochemistry to determine which lake ecosystems are most vulnerable remains challenging. Important but yet not fully understood questions include to what extent different communities, planktonic functional groups, as well as fish populations are able to adapt to CC and how this adaptation capability depends on the rates of gradual changes and on qualitative changes such as shifts in mixing regimes. Nevertheless, a thorough understanding of the effects of CC on physical processes in lakes provided here and how they are modulated by the individual properties of the lake is an indispensable basis to further address these questions.

Take-home messages

- This study is the first explicit simulation of stream and lake water temperature in Switzerland using downscaled projections for all required heat flux variables
- Simulations of river flow and temperature were done only on undisturbed catchments, while lake temperatures were simulated for a set of lakes spanning a wide range of sizes and altitudes
- Mitigation strategies in rivers are promising but require more studies, while CC mitigation in lakes is only feasible in a limited number of hydraulically controlled lakes
- Future CC studies should aim at coupling rivers to lakes, include biogeochemical processes to better assess ecological impacts, and consider anthropogenic usage of rivers and lakes as a base for developing climate adaptation strategies for the management and usage of aquatic systems

7 Conclusions

There is strong evidence that climate warming over the last few decades has had a clear influence on stream and lake temperatures in Switzerland. For the 1979–2018 period, the mean warming rate of streams has been +0.33 °C per decade (for 31 catchments available in this period), and for the 1999-2018 period, the mean warming rate has been +0.37 °C per decade (considering 52 available catchments). In addition, stream temperatures have continued to rise after a noticeable shift observed in 1987/1988. Swiss lakes have warmed at similar rates as other Central European lakes, with average trends since the 1950s of 0.4 °C per decade in the surface waters and 0.1 °C per decade in the deepwaters. Warming is and will remain affected by external and internal factors such as bathymetry, altitude, anthropogenic usage, water clarity, stratification, the surrounding watershed, and local atmospheric conditions including topographic effects.

The observed warming in stream and lake temperature has important consequences both for aquatic communities as well as for ecosystem services. For example, the habitats of some species are shifting upstream to cooler regions, and the warmer conditions favour the spread of diseases in fish, such as the Proliferative Kidney Disease. Lowland lakes have already undergone substantial changes including the loss of winter ice cover, stratification regime shifts, and changes in biological food webs. Also, the high temperatures in rivers and lakes reached during summers are approaching or even passing the current legal limit regarding the release of heat to rivers by the industry. These changes are expected to exacerbate with ongoing CC in the future, where the severity will be determined by greenhouse gas emissions and mitigation strategies.

A significant warming is projected in Swiss rivers by mid-century for both RCP2.6 and RCP8.5. No additional warming is expected by the end of the century for RCP2.6, while an acceleration is projected under RCP8.5. Alpine catchments will experience a moderate warming in winter but a significant warming in summer, reaching +4 °C to +8 °C under RCP8.5 by the end of the century (even larger than the corresponding air temperature warming). This is partially explained by the reduction and ceasing of glacier melt and the related extension of areas of lower albedo. In addition, an important discharge regime shift is expected in alpine catchments, also contributing to the large temperature increase in summer. In lowland catchments, the warming will be also more pronounced in summer, but not in the same proportion as in alpine catchments.

Substantial changes in lake water temperature are to be expected under the business-as-usual scenario RCP8.5. Impacts can be lessened with moderate climate protection following RCP4.5, and substantially reduced yet not entirely eliminated with drastic reduction of emissions as of scenario RCP2.6. Rapid warming and reduction of ice cover duration are expected at high altitudes (~ >1500 m. a.s.l), nevertheless no major physical functional shift is to be expected for these lakes, as they will likely maintain reoccurring ice cover and unchanged stratification regimes. Following substantial past changes at low altitudes, small (<0.5 km^3) and mid to low altitude (~ <1500 m a.s.l.) lakes will be especially sensitive to CC in the coming century, with probable complete loss of ice cover and stratification regime changes.

In order to successfully monitor climate change impacts, and to evaluate mitigation and adaptation strategies in Swiss lakes affected by CC during the 21st century, temperature measurements with a high spatial and temporal resolution will be required (as already existing for the river network). In combination with 1D or 3D coupled river-lake-biogeochemical numerical models, these may be important tools to identify negative effects of CC. Additional work is required to assess the impact and effectiveness of possible mitigation strategies of river temperature warming, such as riparian vegetation shading. Finally, further studies to better understand the complex effects of changing stream temperature and the thermal structure of lakes on aquatic ecosystems, and the cascading effects of changes in the catchments to downstream aquatic systems are required as a basis for developing effective adaptation strategies.

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