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Climate change impact on Swiss hydropower production

Synthesis Report

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Main authors

Wechsler Tobias (WSL, University of Bern)
Stähli Manfred (WSL)

Contributions

Zappa Massimiliano (WSL), Brunner Manuela (WSL), Farinotti Daniel (VAW, WSL),
Björnsen Gurung Astrid (WSL), Grab Melchior (ETH, VAW), Peleg Nadav (ETH),
Schaefli Bettina (Universität Bern), Lanz Klaus (International Water Affairs),
Rickenmann Dieter (WSL), Schirmer Michael (WSL, SLF), Bogner Konrad (WSL),
Boes Robert (ETH), Burlando Paolo (ETH), Guidati Gianfranco (ETH), Hänggi Pascal (Kt. Wallis),
Manso Pedro (EPFL)

Editorial

Gurzeler Sandra (WSL, layout), Annen Jacqueline (WSL, layout), Naeggeli Barbara (ETH, layout),
Dawes Melissa (review)

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Left: Schneider Johannes (WSL) – Water intake at Riedbach (Grächen)
Right: Kappenberger Giovanni – Basodino Glacier and Lake Zott dam

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Climate change impact on Swiss hydropower production: synthesis report

Preface

The recent update of the Climate Change Scenarios for Switzerland – CH2018 (NCCS 2018) – is unambiguous: air temperature will rise in the coming decades because of increasing CO_2 emissions worldwide, and the availability of our water resources will change as a result. For hydropower production in Switzerland, which constitutes the largest share of the nation's electricity production, this implies a modification of "fuel provision", i.e. water runoff to reservoirs and power plants. In addition, climate change will impact the boundary conditions of hydropower production, e.g. by altering the risk of natural hazards or increasing the demand of competing water uses.

These predictions are not completely new. Since at least the 1990s, with the first Swiss National Research Programme on climate change impacts (NRP 31 "Climatic Changes and Natural Hazards", 1993–1997) and later with the first national assessment of climate change impacts on hydropower (Horton *et al.* 2006), the hydropower sector has been aware of the anticipated impacts. The picture became clearer with the publication of a national synthesis in 2010 (SGHL 2011). In the meantime, global climate models, regional glacier models and catchment runoff models have improved, and recent research has generated a better quantitative understanding of relevant geophysical processes. This justifies an updated specification of the current perspectives on hydropower production under climate change.

The focus of this synthesis is on the effects of ongoing global change on water availability and on geomorphic processes and their impact on hydropower production. However, not all direct and indirect consequences of climate change can be considered here, e.g. the impact on energy markets, on the production of alternative renewables and on ecological constraints to hydropower are omitted. These complex feedbacks are explored and discussed elsewhere within the Swiss Competence Center for Energy Research. This document additionally includes possible adaptation measures for sustaining or even expanding current hydropower production to ensure a safe future power supply for Switzerland.

Manfred Stähli

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Climate Change Scenarios CH2018

Climate Change Scenarios CH2018 from MeteoSwiss (NCCS 2018) are based on simulations of 21 different climate models and two different emissions scenarios:

- **(RCP2.6)** Concerted climate change mitigation efforts:
  If efforts are initiated immediately to reduce emissions to virtually zero, the increase in greenhouse gases in the atmosphere can be halted within about 20 years. This will enable the goals of the 2015 Paris Agreement to be achieved, and global warming will be limited to 2 °C compared to pre-industrial levels.
- **(RCP8.5)** No climate change mitigation:
  Mitigation measures are not implemented. Despite technological advances, climate-influencing emissions continually increase – and so does global warming.

The time periods of the Climate Change Scenarios CH2018 are defined as follows:

- **(2060)** Mid-century: "mid-century" or "2060" refers to the period from 2045 to 2074.
- **(2085)** End of the century: "end of the century" or "2085" refers to the period from 2070 to 2099.

Background

The Swiss energy strategy 2050, which includes the planned phase-out of nuclear power plants, increases the pressure on hydropower (HP) production. It expects an increase in annual production by at least 1.5 TWh/a by 2050 while also stipulating the undertaking of profound restoration measures for improving the ecological conditions of rivers. At the same time, the hydropower sector is facing difficult economic and legislative boundary conditions for implementing new plants and reservoirs. In addition, the seasonal demand for HP production is expected to change, with an increasing share in winter to compensate for the discontinuation of nuclear power plants. Against this background, it is becoming increasingly important to know the impact of climate change on the production of the current HP infrastructure in Switzerland.

At present, the Swiss HP system is composed of about 700 powerhouses and 195 large dams. The average annual HP production was 35.7 TWh/a for the period 1980–2016. The spatial distribution of the HP schemes is conditioned by water availability, including the seasonal regimes of rivers, as well as by topography, with most of the storage HP schemes located in the southern and central mountain regions and the large run-of-river (RoR) schemes located around lowland rivers (Schaefli *et al.* 2019). As a consequence, two-thirds of the total HP production originates at Alpine plants, while only one-third is produced in the Swiss Plateau and the Jura Mountains (SFOE 2017). HP is produced in RoR plants, which use the current runoff for power production; in storage power plants, which shift power production from the moment of inflow occurrence to the moment of peak market prices; or in so-called pump-storage systems with price-dependent recirculation of water between lower and higher level reservoirs (Schaefli *et al.* 2015).

Water, the driving force of HP production, is abundant in Switzerland but very variable in time and space. The largest amount of precipitation occurs in the central regions of the Alps, where glaciers and snow cover provide additional water storage for seasonal meltwater supply. However, this water supply can vary from year to year depending on meteorological conditions. For example, during the past 30 years the annual water yield for the power plant Birsfelden, one of the large RoR plants along the Rhine river, fluctuated by +/–35 % [average: ~1040 m^3/s] (the corresponding production yield fluctuated by +/–11 % [average: ~550 GWh/a]). Additionally, the seasonal distribution is highly variable across the seasons, with the largest water supply present during melt conditions in spring. HP depends not only on the availability of water, but also on the dimensions of the power plant and the efficiency of the infrastructure. Further influencing factors are the fine and coarse sediments transported in the stream, which can limit the storage volume of the reservoir and hamper the intake of water. In addition, HP production is impacted by natural hazards, such as floods and mass movements, which endanger structures, reservoirs and areas below the plant.

The above-mentioned natural boundary conditions for HP are altering under ongoing climate change. This trend has become apparent over the past several decades, e. g. with the retreat of glaciers and the diminution of snow cover, and will continue, as outlined in the updated Climate Change Scenarios for Switzerland (NCCS 2018). Air temperature increases in mountain regions will be more pronounced than the global average, mostly due to an albedo effect, which makes mountain systems more susceptible to climate change than other regions. The scenarios make it clear that these trends will persist even if stringent measures for climate protection are implemented worldwide. For HP the most relevant changes will be: a) continued glacier retreat and degradation of frozen soils, b) more frequent flood events, c) more rain and less snow in winter and d) drier summers. As the use of HP involves long-term investments (a concession period is around 80 years), it is particularly important that power plant operators take climate change into account in their work.

In order to assess the various consequences of climate change on natural drivers and related boundary conditions for HP production, the Swiss Competence Center for Energy – Supply of Electricity (SCCER-SoE) established a task group including experts from various national research institutions with specific knowledge on glaciers, snow cover, sediments and hydrology. The goal of the present synthesis report is to summarize the key findings of the publications that emerged from the SCCER-SoE during the past years and assess the integral impact of climate change on HP production in Switzerland. A second objective is to identify possible adaptation measures.

A report with the same title and a similar structure was published in 2011 (SGHL 2011). Since then, various studies have been carried out and additional knowledge has been gained, e. g. from radar measurements of glacier masses. New topics are addressed in the present report: *natural hazards, competing water use, future power production projections and adaptations.* Another new feature of this synthesis is the consideration of the latest Climate Change Scenarios CH2018. The scenarios are based on 21 climate models, 2 different emission scenarios and 2 different time periods. The Climate Change Scenarios CH2018 refer rather to mean values, although averaged values for extreme temperatures, extreme precipitation events and drought indicators are also included. The hydrological modelling was done with a single model (PREVAH). It is important to stress that there is uncertainty across the entire model chain, from the emission scenarios down to the hydrological model and its downscaling methods. This fact must be taken into account when reading and interpreting this synthesis.

1 Precipitation and evaporation

Precipitation is the main driver of hydropower (HP) production. The average annual precipitation in Switzerland is around 1460 mm, of which about 470 mm evaporates and about 990 mm runs off. Climate change will affect not only air temperature, but equally precipitation, evaporation and the entire hydrological cycle, with direct consequences for HP production.

Precipitation

The average precipitation in Switzerland of 1460 mm per year says little about regional conditions. Precipitation processes are decisively influenced by the Alps. Between valley floors and mountain summits, windward and leeward aspects, and the north and south sides of the Alps, there is a multitude of precipitation conditions. On the north side of the Alps, annual precipitation increases by about 70–80 mm per 100 m elevation. The zone with the highest rainfall runs along the northern edge of the Alps, with the maximum precipitation occurring in the Bernese and Valais Alps. Above-average precipitation also occurs throughout Ticino. The seasonal distribution of precipitation in Switzerland is quite balanced (Spreafico and Weingartner 2005).

- **Average precipitation on a large scale will change on a seasonal but not annual level.**
- **Winter precipitation will increase by up to 24 % and summer precipitation will decrease by up to 39 % by the end of the century.**
- **Higher temperatures will not necessarily lead to a nationwide increase in evaporation but could cause significant water loss locally (up to 6 mm per day).**

The average annual precipitation is predicted to remain about the same for most areas in Switzerland, whereas winter precipitation is expected to increase by up to 20 % by mid-century and by up to 24 % by the end of the century, and summer precipitation is expected to decrease by up to 25 % (39 %) (Fig. 1).

Molnar *et al.* (2015) indicated that heavy precipitation is expected to intensify with higher air temperatures. According to the CH2018 scenarios, extreme daily precipitation is foreseen to increase by about 20 % in winter and by 10 % in summer by the end of the century (NCCS 2018). However, changes to precipitation extremes at the daily to sub-daily scales remain well within the current climate variability (Peleg *et al.* 2017, 2019).

Evaporation

An average of 470 mm of water evaporates every year in Switzerland. With increasing elevation, both potential and actual evaporation decrease by about 22 mm per 100 meters (Spreafico and Weingartner 2005). While potential evaporation increased throughout the year considerably since 1900, actual evaporation has increased significantly in winter and autumn only

Change in precipitation by the end of the century

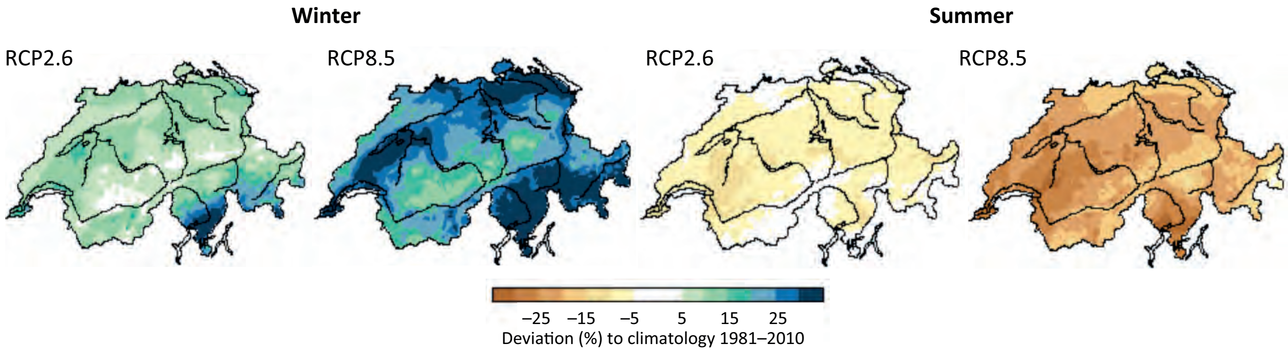


Fig. 1. Winter (left – DJF) and summer (right – JJA) precipitation by the end of the century for the emissions scenarios RCP2.6 and RCP8.5 (NCCS 2018).

(Kummer 2017). Between 1981 and 2010, actual evaporation also increased in spring, particularly in May and June. This could be related to the decline in humidity and the increase in sunshine duration and radiation. Furthermore, higher temperatures are partly responsible for the increase in actual evaporation. However, actual evaporation depends on water availability. Thus, the actual evaporation over a large area can be very small, while in specific locations, for example in lakes, the actual evaporation can be very large. During hot days in 2018, evaporation from Lake Constance was estimated at 5 mm/day. When extended to reservoirs, this can contribute to a noticeable water loss.

In the future, an increase in actual evaporation during autumn, winter and spring is expected (Brunner *et al.* 2019). In autumn, the soil will remain snow-free for a longer time, and in spring the snow will disappear earlier. Even during the winter months, especially at low elevations, no-snow situations will occur more frequently. This change in the cryosphere and thus in albedo will cause an increase in actual evaporation, which will be particularly evident in the second half of the century (Fig. 2).

Importance for Hydropower

The minor changes in mean annual precipitation and evaporation are not expected to substantially modify HP production, whereas the increasing probability of extreme rainfall events (rain storms and droughts) will likely be more important. Hydrological simulations show that future inflow variation across the seasons will be even more pronounced than variation among years: less summer (June-July-August; JJA) discharge, mainly explained by a decrease in summer precipitation, and more winter (December-January-February; DJF) discharge is projected (Savelsberg *et al.* 2018). More winter precipitation will have a positive impact on Swiss power plants, as less water needs to be spilled (Savelsberg *et al.* 2018). Run-of-river (RoR) power plants are expected to have greater winter production and more run time by the end of the century. This could possibly have an impact on the timing of revision work. Surprisingly, RoR plants will benefit more from climate-induced changes despite their lower flexibility, potentially because of their currently unused capacity during winter peak periods (Savelsberg *et al.* 2018). For storage power plants, the amount of unused capacity is almost zero and their full capacity during winter peak periods is thus already reached.

Change in actual evaporation by the end of the century

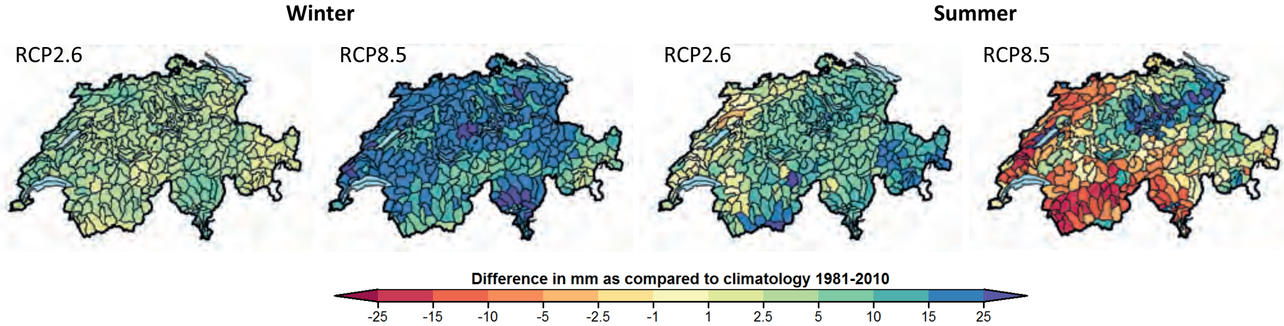


Fig. 2. Winter (left - DJF) and summer (right – JJA) actual evaporation by the end of the century for the emissions scenarios RCP2.6 and RCP8.5 (Based on data by Brunner *et al.* 2019).

2 Glaciers and snow

Meltwater from Alpine glaciers and snow cover are key components of the Swiss hydrological budget and not least for Swiss hydropower (HP) production. The two components provide a natural reservoir of fresh water by storing precipitation, filling aquifers and delaying runoff. Meltwater also contributes significantly to total discharge, shapes seasonal regimes, and especially sustains minimum flow levels during dry periods. Usually, rivers at low elevations are only marginally or temporarily influenced by snow contributions, whereas snow (ice) dominated catchments experience peak runoff in May and June (July and August), with values more than double the mean annual runoff. By the end of the century, it is anticipated that the volumes of snow and ice stored in the Alps will decrease significantly because of climate change.

Glaciers

The Swiss Glacier Inventory (SGI) refers to a total of 1420 glaciers in Switzerland, with an estimated total ice volume of 59.9 km^3 for the year 2010 (Fischer *et al.* 2015). In the framework of SCCER-SoE, the ice thickness of large parts of the Swiss glaciers have been surveyed with ground penetrating radar (Langhammer *et al.* 2019a) additionally to the previously surveyed glaciers (Fig. 4, left). Using these data and the newest available digital elevation model, the total ice volume is currently estimated using the approach of Langhammer *et al.* (2019b; Fig. 4 right) to be around 53 km^3 (work in progress).

- **Swiss glaciers will lose between 76 % and 98 % of their current ice volume by 2100.**
- **At the end of the century, the glacier melt contribution to runoff in the Swiss rivers will be virtually non-existent (today: 2 % at Rhine Basel, 13 % at Aare Brienz).**
- **HP production could fall by 0.56 TWh/a (1 TWh/a) by mid-century (end of century), owing to lower glacierization.**

Fig. 3. The development of the Rhone glacier from 1850 to the present (VAW-ETHZ 2010).

Swiss glaciers have been losing ice volume since 1850 (Last Glacial Maximum) in response to the warming of the global climate (Fig. 3). By the end of the century, the European Alps will be largely ice-free (Zekollari *et al.* 2019); for the Swiss Alps, a loss between 76 % and 98 % of their current ice volume is expected (Ayala *et al.* 2020). At the same time, bare areas will emerge at high elevations, which will potentially be usable for new water reservoirs.

Today, the ice-melt contribution to runoff has a certain importance even for lowland run-of-river (RoR) plants. The average glacier contribution to major Swiss rivers in the month of August varies between 2 % for the Rhine (Basel) and 47 % for the Rhone (Chancy) (Huss 2011). The closer a catchment is to a glacierized environment, the stronger it is affected by glacier retreat. The main contribution of ice melt is during late summer, when the seasonal snow cover has been depleted and precipitation is limited. No glacial ice melt contributes to runoff in winter (Stahl *et al.* 2016).

From a hydrological point of view, the process of glacier retreat is expected to occur in two stages. Initially, the air temperature increase will cause enhanced ablation, thus leading to a temporary increase in the annual discharge of Alpine rivers. In the long term, however, and once the glacier has shrunk considerably, annual und summer discharge from Alpine headwaters will decrease, owing to the reduced ice volume and meltwater.

Importance for Hydropower

The timing of peak water is an important question for HP production. At peak water the total runoff and HP production for a given catchment is maximal. After this point production decreases because inflow reduces. The timing of peak water is still uncertain and depends strongly on catchment properties. Recent studies about the Alps indicate that this region can be expected to reach peak water in the first half of the 21st century (Huss and Hock 2018).

Swiss glaciers will lose a large part of their current volume. Reduced glacier melt is likely to have a signifi-

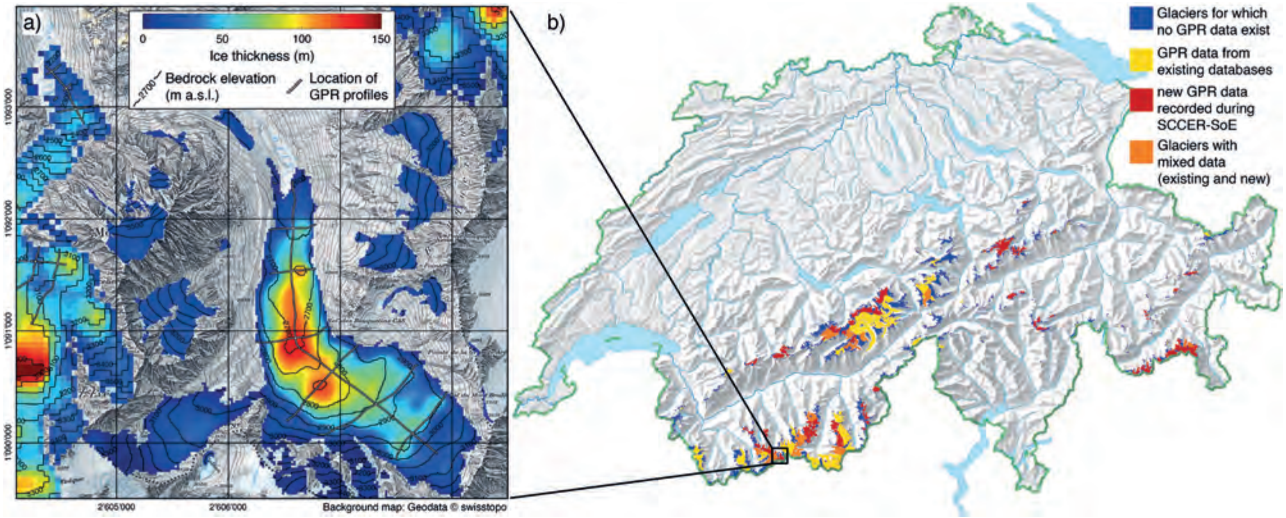


Fig. 4. a) Ice thickness of Haute Glacier d'Arolla, which is a section of the Swiss-wide ice thickness- and bedrock topography map obtained with the approach of LANGHAMMER *et al.* (2019b), using (b) all available ice thickness data measured with ground penetrating radar (GPR).

cant impact on HP production (FATICHI *et al.* 2015). HP production could fall by 0.56 TWh/a by mid-century and by 1 TWh/a by the end of the century, owing to lower glacierization (SCHAEFLI *et al.* 2019). PAUL *et al.* (2011) calculated that almost 500 new lakes, with a total area of 50 km^2 and a total volume of 2 km^3, could form in today's glacierized areas. This corresponds to about half of the volume of all current Swiss HP reservoirs. Lakes can be an interesting opportunity for HP generation and can have effects similar to those of glaciers in terms of water storage. Whether a particular site is suitable for potential reservoirs depends on topography, access, sediment flow, specific protection interests (e. g. floodplain areas) and other local features (EHRBAR *et al.* 2018).

Snow

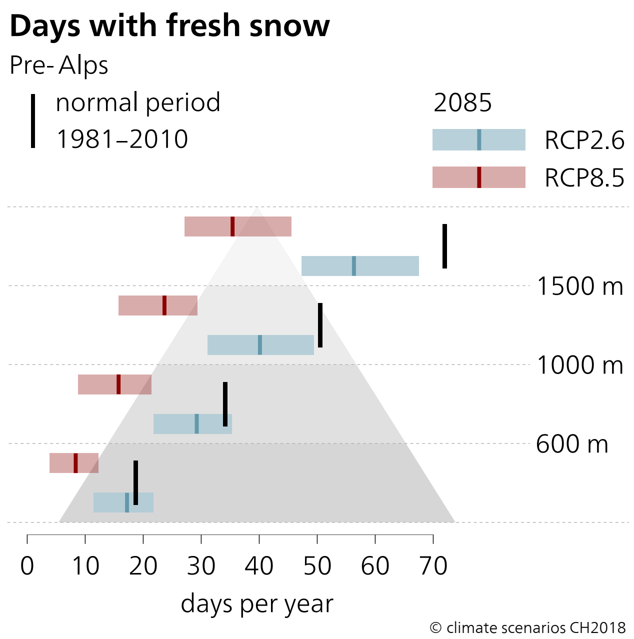
The timing, thickness and spatial coverage of snow cover is a result of temperature and precipitation. In the Swiss Alps, the three variables (timing, volume, extent) have shown negative trends over the past decades (MARTY *et al.* 2017b; DURAND *et al.* 2009; TERZAGO *et al.* 2013). The trends are elevation dependent, with more (less) distinctive changes at low (high) elevations. Climate-change-induced warming already reduces snow accumulation because of a greater fraction of precipitation falls as rain. Moreover, warmer spring and summer temperatures intensify spring snowmelt in the Alps and thus cause a shift to earlier snow disappearance. Areas below 1200 m a.s.l. will be most affected by climate change: almost no snow is expected towards the end of the century (MARTY *et al.* 2017b). For regions above 1200 m a.s.l., a decrease in seasonal snow cover duration by 25 days per degree warming is expected (SHGL 2011). The days with fresh snow, even in regions above 1500 m a.s.l., will decrease by 15 days under the RCP2.6 emissions scenario (30 days under RCP8.5) (Fig. 5) and spring snow water equivalent (SWE) also shows a decrease (MARTY *et al.* 2017a). These changes will lead to less variability between snow-scarce and snow-abundant winters than today.

- **In the future, higher temperatures in the Alps will change the precipitation type from solid (snow) to liquid, which will in turn lead to more direct runoff in winter.**
- **Above 1400 m a.s.l. RoR winter-production could increase by over 30 %.**
- **The timing of melt peak will shift towards earlier in spring and melt volume will be smaller as a result of reduced snow storage.**

The relative snowmelt contribution to runoff strongly depends on elevation. At 1500 m a.s.l. (2000 m a.s.l.) snowfall currently contributes about 30 % (50 %) to the annual precipitation sum (MARTY *et al.* 2020). Snowmelt also contributes to low-elevation river systems, such as the Rhine (Basel), where the mean annual fraction of snowmelt is estimated to be around 40 %, compared to only 2 % originating from glacier melt (STAHL *et al.* 2016). This shows the importance of snow as a runoff component for RoR power plants even at low elevations, especially during the hot and dry summer season. This influence will be profoundly reduced, owing to the projected elevation-dependent reductions in snow volume between 50 % and 97 % by 2100 (MARTY *et al.* 2020). On the basis of long-term SWE measurements, a clear decline, especially in spring, is expected. The loss since the 1960s ranges from 80 % below 1000 m a.s.l. to about 10 % at 2500 m a.s.l. for 1 April. Towards the end of the century, a relative reduction in mean SWE by about 70 % is projected for typical large Alpine catchments (Marty *et al.* 2017a). In the future, higher air temperatures in the Alps will change the precipitation type from solid (snow) to liquid, which in turn will lead to more direct runoff in winter (Addor *et al.* 2014).

Importance for Hydropower

The snow-cover change will affect the seasonal distribution of RoR production and postpone the replenishment of Alpine HP reservoirs. By mid-century, the amount of RoR production above 1400 m a.s.l. in normal years could increase by over 30 % during the winter months (Schaefli *et al.* 2019). In low- and mid-elevation areas, precipitation will fall as rain instead of snow. This is favourable to meet the high winter electricity demand. On the other hand, snowmelt is projected to occur earlier in the season and exhibit a decline. This implies that runoff will be less variable over the year and can be seen as a positive effect for HP use in high-elevation catchments. On the other hand, the above-mentioned reduction in summer runoff could affect HP production in low-elevation regions. The reduction in summer runoff implies that some mountain rivers may no longer be able to maintain sustained discharge during prolonged dry spells, and low-runoff situations may become more common in low-elevation regions.



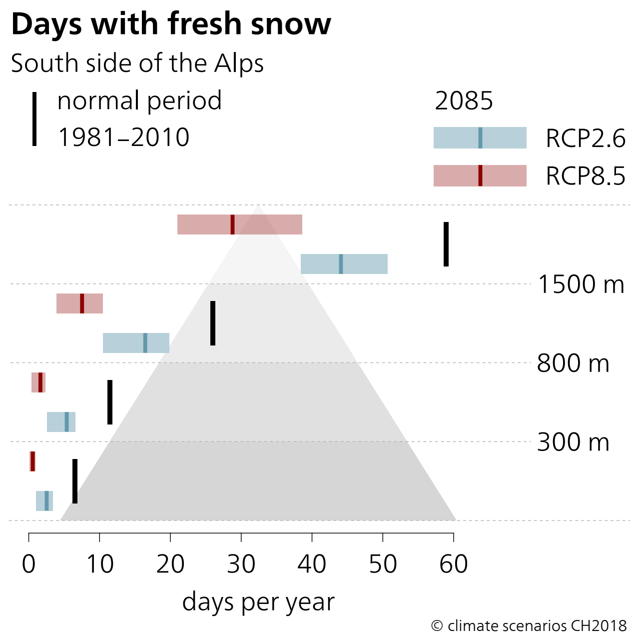


Fig. 5. Days with fresh snow at different elevations in the Pre-Alps (left) and the south side of the Alps (right) for the period 2085 and emissions scenarios RCP2.6 (blue) and RCP8.5 (red) (NCCS 2018).

3 Sediments

Sediments transported in streams and rivers are relevant for hydropower (HP) production because they impair the functioning of infrastructures, especially turbines. Reservoir storage capacity reduces every year because of sedimentation. Climate change will increase sediment availability as a consequence of the expansion of proglacial areas and the thawing of permafrost. On the other hand, sediment transport capacity in streams will decrease in the long term, owing to a declining snowmelt contribution to runoff and prolonged low-flow periods. The impact of climate change will differ for coarse and suspended sediments. Changes in climate, sediment availability, release and connectivity may cause various evolutions in time and between systems, which are difficult to predict and strongly depend on local features.

Sediment availability

- **In Alpine areas, glacier retreat, shrinking permafrost and shorter snow cover will lead to greater sediment availability.**
- **In lower areas, i. e. in the Pre-Alps and Swiss Plateau, sediment production will change due to anthropogenic effects rather than due to climate change.**
- **Suspended sediment causes abrasion on HP infrastructure; maintenance is likely to be required more frequently.**
- **In Switzerland, 0.2 % of the annual storage capacity is lost through continuing sedimentation.**

In terms of sediment availability, climate change will have a significant impact. Retreating glaciers typically leave behind large amounts of loose sediment, while shrinking permafrost destabilizes loose material and soil. In the future, Alpine catchment areas will be more severely affected by hillslope erosion driven by overland flow and rainfall erosion, owing to less permanently frozen ground (Quinton and Carey 2008). This process will intensify during summer and autumn, when Alpine catchments are largely free of snow and extreme rainfall can erode large amounts of sediment. Intense rainfall may even trigger natural hazards like rockfalls, debris flows and landslides. Such events can deliver a large mass of sediment to the channel network (Bennett *et al.* 2012). These processes are expected to increase in frequency (Stoffel and Beniston 2006; Staffler *et al.* 2008; Jakob and Lambert 2009; Huggel *et al.* 2012) and thus increase the sediment availability at high elevations.

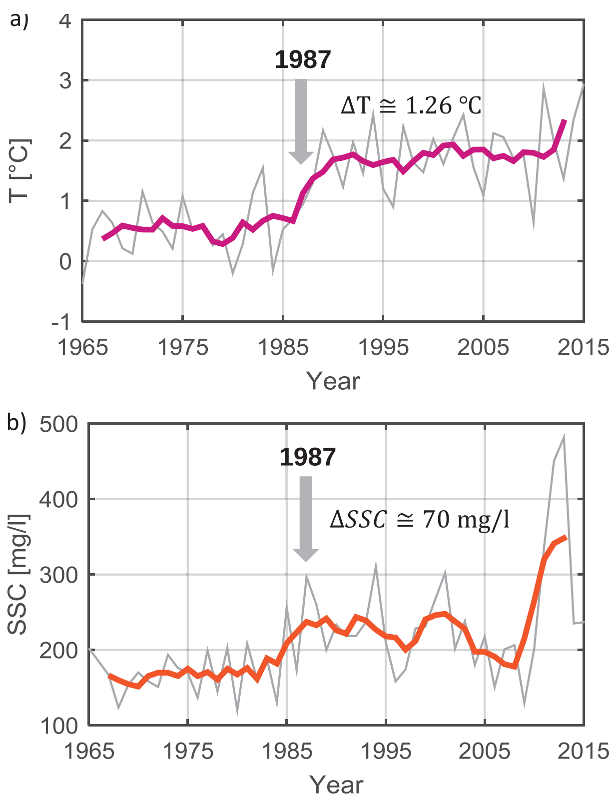


Fig. 6. Observations for the period 1965–2015 of: a) basin-averaged air temperature and b) suspended sediment concentration measured at the outlet of the basin. Mean annual values are shown in grey and the 5-year moving average is shown with a bold line (Costa *et al.* 2018: 519).

Suspended sediment yield

A decrease in snowfall days, snow-cover duration and snow depth has an impact on sediment yield (e. g. Beniston 1997; Laternser and Schneebeli 2003; Scherrer *et al.* 2004; Marty 2008; Scherrer and Appenzeller 2006). High summer temperatures cause high rates of glacial melt. Meltwater releases sediment and provides enhanced flow to transport sediment (Lane *et al.* 2017). The suspended sediment concentration is strongly dominated by temperature-driven ice melt. This leads to a step-like increase in the suspended sediment concentration at the outlet of the catchment (Costa *et al.* 2018). A temperature increase of more than 1 °C in the years 1987–2015 compared to 1965–1986 (Fig. 6) led to an increase in the mean suspended sediment concentration of about 70 mg l^{-1} (i. e. a 40 % increase) at the outlet of the total Valais basin during the summer months (Costa *et al.* 2018). In glacierized catchments, bedload transfer occurs continuously over the warm summer months (Turowski *et al.* 2011). Currently, bedload transport in glacierized catchments is less influenced by individual extreme precipitation events than in unglacierized catchments. However, owing to less snowmelt and a reduced extent and duration of snow cover, the suspended sediment concentration may increase through enhanced erosion by heavy rainfall events over snow-free surfaces (Costa *et al.* 2018). Meltwater does not only contain sediments from the glacier forefield: NRP70 shows that up to 70 % of the suspended sediment can be eroded directly under the glacier (Boes *et al.* 2020).

Transport of coarse sediments

The sediment and bedload transport capacity along rivers is determined by the flow conditions (Fig. 7). Due to an increasing number of extreme events at high elevations in the future, a higher transport capacity is expected. In addition, an increase in winter rainfall, with more frequent floods, will result in a higher transport capacity (Raymond-Pralong *et al.* 2015). Increased sediment availability and a temporary increase in runoff from sediment-rich proglacial areas will lead to more sediment transfer by mid-century (Costa *et al.* 2018). By the end of the century, less ice melt and less summer snowmelt could weaken continuous sediment transport in summer (Bakker *et al.* 2017). Models have shown a long-term decrease in sediment yield resulting from reduced runoff during summer and a significant time shift of the seasonal sediment transport to earlier months of the year. Further simulations have shown a significant difference in bedload transport between winter and the snowmelt season: as bedload transport relies on thresholds of discharge, by mid-century one can expect higher bedload fluxes in winter but lower bedload fluxes in April to June. If more intense or more frequent rainstorms are expected in the future, the corresponding increase in sediment transfer may exceed the predicted decrease resulting from reduced glacier runoff. Moreover, climate-induced changes in sediment delivery over the next few decades are still uncertain in the lower elevations of the Alps. However, they are likely to be more subdued in large lowland rivers than in glacierized catchments.

Fig. 7. The net sampler used for the calibration measurements at the Albula river (Photo: Tobias Nicollier).

Importance for Hydropower

Sediment delivery is known to have a significant impact on HP infrastructures and vice versa (Schaefli *et al.* 2007). Flow abstraction schemes for HP differ from classical reservoir schemes in that they ensure sediment delivery through intermittent purges. Residual transport rates may still be sufficient to maintain significant sediment transfer even though flow abstraction in Alpine streams may lead to a notable reduction in bedload transport capacity. Sediment supply and the residual sediment transport capacity are a function of the number of purges (Bakker *et al.* 2017). Therefore, flows (discharge and duration) are required to empty the sediment traps. The evolution of floods under climate change is dealt with in the next chapter (natural hazards).

Suspended sediments cause abrasion on turbines and pumps. As suspended sediment concentrations increase in the near future, maintenance is likely to be required more frequently, affecting runtimes. HP plants at large lowland rivers will be less significantly affected by bedload development, as the effect will be more subdued due to their location.

The sedimentation of storage reservoirs and balancing basins can lead to capacity loss, which is a current concern in operational management (Schleiss *et al.* 1996; Morris and Fan 1998). In Switzerland, on average 0.2 % of the annual storage capacity is lost with continuing sedimentation (Schleiss *et al.* 2010). The storage capacity loss has a negative impact on HP production, flood protection and water availability. However, long-term predictions indicate a decrease in sediment loads because of reduced glacier runoff. This decrease will be advantageous for hydroelectric power plants, as it will lead to a reduction in purging operations at the intakes and less rapid aggradation in reservoirs (Raymond-Pralong *et al.* 2015).

4 Natural hazards

Hydropower (HP) plants and other HP infrastructures are highly exposed to natural hazards, owing to their location in Alpine areas. Dam safety management has generally been carried out assuming stationary climatic and non-climatic conditions. With climate change, the frequency, intensity and seasonality of natural hazards is expected to change. An increase in heavy precipitation events raises the risk of floods, and the melting of permanently frozen Alpine areas will be accompanied by more frequent natural hazards.

High-Alpine natural hazards

- **Slope instabilities and exposure to previously ice-covered terrain could lead to increased mass mobilization, potentially causing floods, rockfalls and landslides.**
- **Climate change is likely to influence the frequency, intensity and seasonality of landslide activations, rockfalls, debris flows, wet snow avalanches and floods.**

High-Alpine natural hazards, such as rockfalls, debris flows, glacier collapses and GLOFs (Glacier Lake Outburst Floods) are multidimensional and non-linear dynamical processes with complex occurrences in space and time (Fig. 8). In the past, such processes have threatened and occasionally caused heavy damage to HP plants, both during construction – e.g. Mattmark in 1965 with 88 fatalities (Pfister 2009) – and operation – e.g. Vajont Dam in 1963 with 2000 fatalities (Genevois and Prestininzi 2013). Many mass movement processes are related to steep topography and geological and cryospheric predisposition. Freeze–thaw cycles in spring (Stoffel *et al.* 2005a), but also heavy rainfall (Schneuwly and Stoffel 2008), are typical triggers of natural hazards.

The impacts of climate change with regard to natural hazards are most evident in higher-elevation permafrost-dominated environments, where more and larger events were recorded in the past (1720) and during the heat wave in summer 2003 (Gruber *et al.* 2004; Stoffel *et al.* 2005b). Retreating glaciers and dwindling permafrost, as well as a possible accumulation and intensification of heavy rainfall events in spring and autumn, are likely to locally increase the number (and possibly also the size) of rockfalls in the future. Glacier-related hazards, such as GLOFs or the temporary damming of proglacial streamflow through mass movements, are also likely to

Fig. 8. Size of the debris cone in the Swiss village of Bondo in 2018 after the Piz Cengalo rock avalanche (Photo: SRF).

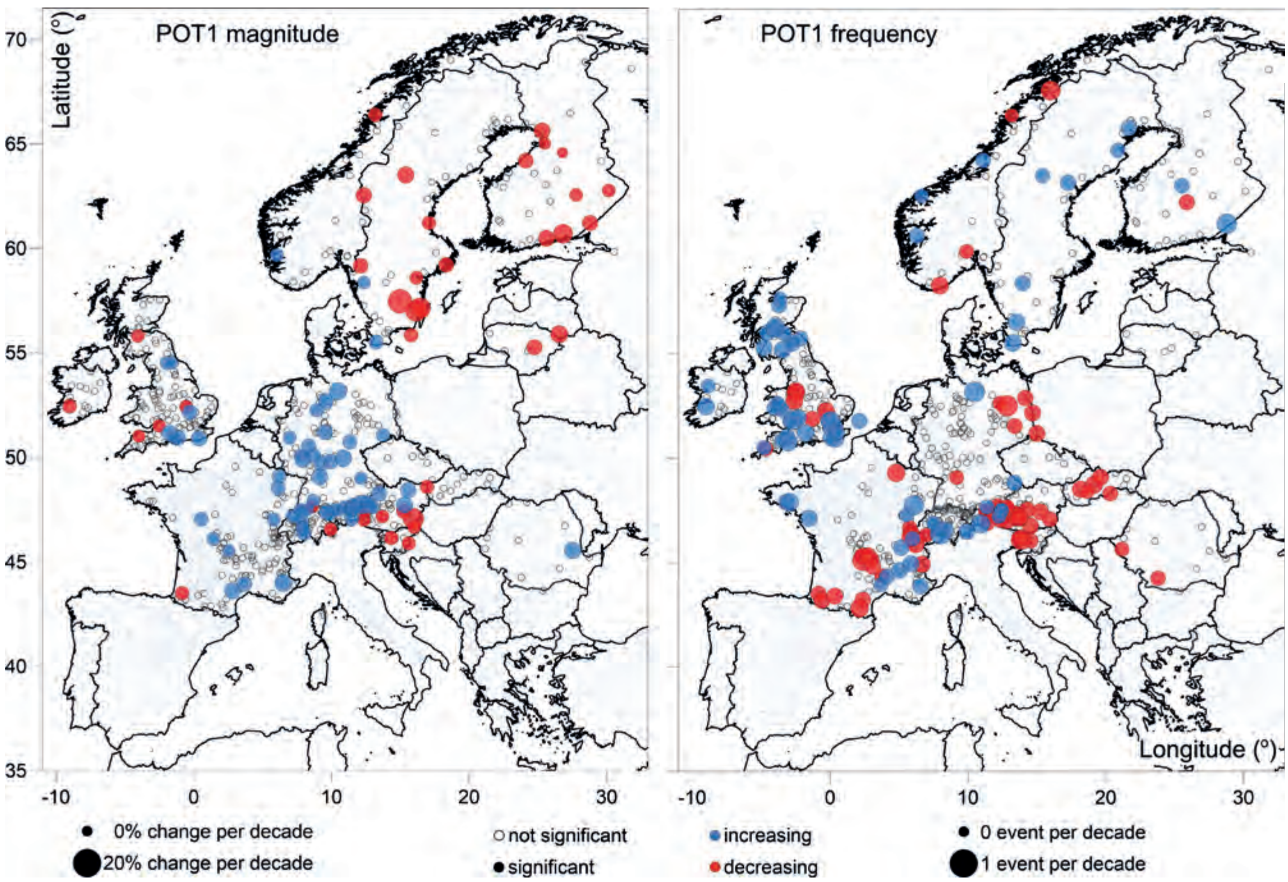


Fig. 9. Trends in flood magnitude (left) and frequency (right) in Europe. Filled symbols indicate statistically significant positive (blue) and negative (red) trends at the 10 % level of significance. Symbol size indicates: (left) the change in the mean flood magnitude exceeding the threshold, expressed in % per decade; or (right) the change in the mean number of floods exceeding the threshold, expressed in events per decade (Mangini *et al.* 2018: 10).

increase in the future as considerable changes occur in Alpine environments (Stoffel *et al.* 2014; Huss *et al.* 2017). Proglacial lakes carry the risk of sudden water release, with potentially catastrophic consequences (Frey *et al.* 2010; Worni *et al.* 2014; Haeberli *et al.* 2016). Slope instabilities, glacier retreat and exposure to previously ice-covered terrain could lead to increased mass mobilization, which could affect the incidence of floods and landslides (Beniston *et al.* 2011; Stoffel and Huggel 2012; Huss *et al.* 2017). Furthermore, climate change is likely to influence the frequency, number and seasonality of landslide activations and debris flows (Stoffel *et al.* 2014), as well as the risk of wet snow avalanches (Pielmeier *et al.* 2013).

Flood hazard

The seasonality of floods in Europe has shown a clear shift during the past 50 years (Blöschl 2017). Regional trends in the highest annual flood peak occurrence range from –13 days per decade for earlier floods to +9 days per decade for later floods. Over 50 years this means a total shift of –65 or +45 days. This is caused on the one hand by higher temperatures, which lead to earlier spring snowmelt floods in spring, and on the other hand by delayed winter storms in connection with polar warming, which lead to later winter floods. In addition, earlier soil moisture maxima have led to earlier winter floods. Rapid snowmelt together with heavy rainfall can lead to considerable runoff or floods. Weingartner *et al.* (2003) suggested that flood risk is reduced in areas >2000 m a.s.l. because of short-term storage of precipitation as snow cover. Wehren *et al.* (2010) demonstrated that this threshold is slightly lower, at 1800 m a.s.l., and Köplin (2014) stated that the upper limit of the flood-prone zone is 1000 m a.s.l. The future frequency and intensity of rain-on-snow events and associated fast runoff is uncertain (Würzer and Jonas 2017), but according to Beniston and Stoffel (2016) rain-on-snow events could increase in the future despite reduced snow cover.

The intensity and frequency of floods in general are predicted to shift under climate change. A number of studies suggest that higher temperatures provoke higher water holding capacities of the atmosphere and therefore a higher probability of extreme precipitation events (Boroneant *et al.* 2006; Beniston 2012). The anticipated increase in heavy precipitation will result in an increased flood risk (Köplin 2014). Mangini *et al.* (2018) showed that the picture of flood change in Europe is strongly heterogeneous and no general statements about uniform trends across the entire continent can be made (Fig. 9). Regional patterns of marked flood trends do exist, but it has not yet been possible to identify a consistent climate-change-induced large-scale signal in flood magnitudes (Blöschl 2017).

Importance for Hydropower

Changes to high Alpine mass movements and floods will affect the vulnerability of infrastructures and a range of economic services (Beniston *et al.* 2011). A dam failure or malfunction has serious consequences, as the resulting water volume could not be managed. A slope failure event near a dam site could entail a part of the terrain falling into the reservoir or impacting the dam. Consequences could be an overtopping of the dam or even a dam failure. A similar hazard risk is assumed in glacial and periglacial environments, where rising temperatures lead to a decrease in the thickness and extend of glaciers and a progressive degradation of permafrost. The thermal disturbance can cause stress redistribution and rapid changes in mechanical conditions at depth (Schneider *et al.* 2011) and increase the risk of rock avalanches or glacial lake eruptions (GLOFs) entering the reservoir (Evans and Delaney 2015; Huggel *et al.* 2008; Stoffel and Huggel 2012). In general, it is important to examine how the dimensioning variables (e. g. floods and earthquakes) and hazard maps will become altered with climate change so that critical power plants can be identified.

During a flood event, HP operation is stopped at a certain point of discharge in order to avoid damage to the infrastructure. Hänggi and Weingartner (2012) used the Q_2 percentile of the frequency distribution to define this limit. A comparison with the power plants from chapter 6 shows that the change in Q_2 value from the reference period (1981–2010) to the end of the century (2070–2099) under the considered Climate Change Scenarios means that power plants (with unchanged installed machinery) will experience:

- up to 6 days/a HP operation in strongly glacierized catchment areas
- reduced operation by about 1 day/a along large lowland rivers

Further, rising temperatures and solar exposure can pose a hazard to the structural behaviour of concrete dams (Malm 2016). Temperature variations mean additional mechanical stresses for the dam, making it more susceptible to hydrostatic loads. In addition, the potential variation in stored water in the reservoir can increase the exposure of the dam body to solar radiation and cause larger temperature differences, as well as higher temperature peaks in the concrete surface. More frequent changes in storage levels could reduce soil moisture and thus increase the susceptibility of dams to processes such as internal erosion. Moisture content plays a key role in internal erosion properties: as the water content decreases, the critical shear stress declines and thus the soil resistance to erosion worsens (Wan und Fell 2004).

5 Competing water use

Climate change will not only alter the natural water supply for hydropower (HP), but also have an impact on the water demand of competing sectors, such as agriculture, industry and tourism. This water demand is much smaller than the amount of water used for HP production, and it relates largely to the Plateau region. The total water demand in Switzerland is highest in winter, owing to the strong influence of hydroelectric power production, whereas demand for agricultural irrigation is highest during dry summers. In the future, water deficits are likely to become more frequent because of increases in competing water uses (Fig. 10).

Irrigation

In a normal year, agricultural irrigation is estimated to use 280 million m^3 of water, approximately 20% of the water volume used for HP production (Brunner *et al.* 2019). The spatial distribution of this water demand is very heterogeneous; whereas the water demand for HP and artificial snow is particularly important in the Alpine valleys, other competing water uses are more important in the Plateau region. Most of the agricultural irrigation takes place from April to September and, thus, does not overlap with electricity production from storage power plants. At times when a lot of water is needed for irrigation, relatively little water is needed for electricity production. Yet, in extraordinarily dry years, such as 2018, the total amount of water needed for irrigation can be significantly higher. In addition, water demand strongly depends on the crop, such as vegetables, fruits and grass. Owing to climate change, the demand for irrigation is expected to almost double, reaching up to 500 million m^3, by the end of the century.

- **Climate change can lead to more frequent water deficits.**
- **Storage power plants can become more important through regulatory services.**
- **Multipurpose uses of HP reservoirs have little impact on the annual production rate, but they can have an impact on the production pattern and the annual revenue.**

Artificial snow production

Due to climate change and the resulting changes in conditions in Swiss ski resorts, artificial snow production has increased sharply. In winter 2015/2016, 49% of all ski slopes were covered with artificial snow (Jossi 2019). An estimated 1.5 million m^3 of water is used for the production of artificial snow (Brunner *et al.* 2019). A large part of this water comes from snow-making ponds. In total, around 4 million m^3 of water is held in these ponds (Brunner *et al.* 2019). Water for artificial snow production is taken from HP reservoirs in only a few cases, e.g. Lac des Dix.

In the future, increasing demands for snow reliability throughout the winter season will increase the water demand for artificial snow production. On the other hand, higher temperatures and a rising elevation for the 0 °C threshold will make the operation of winter sports facilities below 2000 m a.s.l. very difficult or even impossible. Assuming that these areas will stop producing snow towards the end of the century, the Swiss water demand for snow production is estimated to increase only slightly, by up to 0.5 million m^3 (Brunner *et al.* 2019).

Ecosystem conservation

Estimating the water demand for nature or ecosystem conservation is very difficult. To protect humans, animals and plants from adverse impacts the Swiss Water Protection Act (WPS) intends to preserve natural habitats for native flora and fauna, in particular fish-bearing water bodies and water bodies as elements of the landscape. To mitigate the negative impacts of a HP reservoir, continuity (ascent and descent) for living organisms, bedload transport, natural flow dynamics and an appropriate amount of residual flow must be taken into account. For the eleven run-of-river (RoR) power plants considered in the following chapter (6), compliance with the residual flow rate, compared to no residual flow, means a production loss of under 4% (112 GWh/a).

Flood protection

In some cases, HP reservoirs are already used as a flood protection measure. After the flood event of September 1993 in the Saas Valley, flood protection was reassessed. The overflow edge was raised by 2 m, while the dam target remained at the same height. With the additional volume created, the flood peak was greatly reduced and delayed. Technical adjustments to the raised section have a further delaying effect. In addition to structural measures, better meteorological forecasts help to counter the risk of flooding by operating reservoirs.

Fig. 10. Interactions between pump-storage power plants and the environment, economy and society (JOSSEN and BJÖRNSEN GURUNG 2018: 109).

Fire-fighting water

Currently, several HP reservoirs are being used as a precautionary measure against fire hazards, including forest fires, to secure fire-fighting water. In the canton of Valais, where drought and forest fire hazards may exist temporarily, reservoirs such as Lac de Mauvoisin, Tseuzier, Toules and Gibidum are used for this purpose.

Water for households and industry

The water requirements of households and industry are not discussed in this chapter, as water for these purposes is hardly ever supplied from HP reservoirs in Switzerland, owing to the natural conditions. This situation is unlikely to change in the future (BRUNNER *et al.* 2019).

Importance for Hydropower

HP reservoirs in Switzerland may be required to provide additional services in the future. Especially in dry periods, the demand for multipurpose uses can be expected to increase significantly, for example for agricultural irrigation. Additional uses will hardly change the total amount of electricity production by storage power plants, but they will likely modify the production pattern and the revenue under today's conditions. However, a rising demand for services will also have an impact on the price. Nevertheless, concessions and possibly some regulations may be adjusted in order to regulate competing water uses under climate change.

6 Climate change impact on run-of-river power production

As discussed in the previous sections of this report, the runoff regime of Swiss rivers will be modified by climate change. This will directly alter the seasonal and annual production of run-of-river (RoR) power plants, as they do not have storage capacities. The change in power production can be estimated by a flow duration curve (FDC). For 11 RoR power plants across Switzerland, representing different elevations, flow regimes and climatological regions, the FDC was calculated for the current and future climate (CH2018 scenarios) using a state-of-the-art hydrological model (PREVAH), assuming present-day installed machinery and residual water flow requirements.

- **By mid-century, annual RoR production will remain roughly the same; winter production will increase by about 5 %.**
- **By the end of the century, annual RoR production will decrease slightly; winter production will increase by about 8 %.**

FDCs can be used to estimate the yearly (or half-yearly) power production of a RoR plant with a given installed capacity (HÄNGGI and WEINGARTNER 2012). In a FDC, all daily runoff values of a given RoR plant are ordered by size and frequency distribution, resulting in a concave shape (Fig. 11). The shaded area represents the volume that can be used for power production and is limited by two parameters: Q_d represents the maximum discharge that the power plant can use. Q_{min} is the volume that cannot be used for hydropower (HP) because the minimum turbine height is not reached or because discharge is used for residual flow, irrigation, water supply, ecological flow, fish passages or other purposes. The third parameter Q_{max}, which completely exceeds the range of turbine operation, owing to flooding, is not relevant in this report. Such FDCs can be calculated for a current runoff regime or for future runoff regimes under climate change. In the case of HP generation under climate change, it is not only the change in total annual runoff that is important, but also how the usable volume changes, which depends on the dimensions of the power plant.

Examples of typical Alpine and lowland rivers

The FDC for the reference period 1981–2010 (black) and for the end of the century (2070–2099, yellow and purple) are given in Fig. 12. For the future period, the daily runoff was calculated with a state-of-the-art hydrological model (PREVAH; VIVIROLI *et al.* 2009) using the official Climate Change Scenarios CH2018 (NCCS 2018). The shaded area bounded by yellow lines represents the range of FDCs of the various climate models with concerted mitigation efforts (RCP2.6); the shaded area bounded by purple lines shows the range of FDCs of the models with no climate change mitigation (RCP8.5).The left panel shows values for the Wildegg-Brugg RoR power plant along the Aare, a large Swiss river, where the number of days with low flow tends

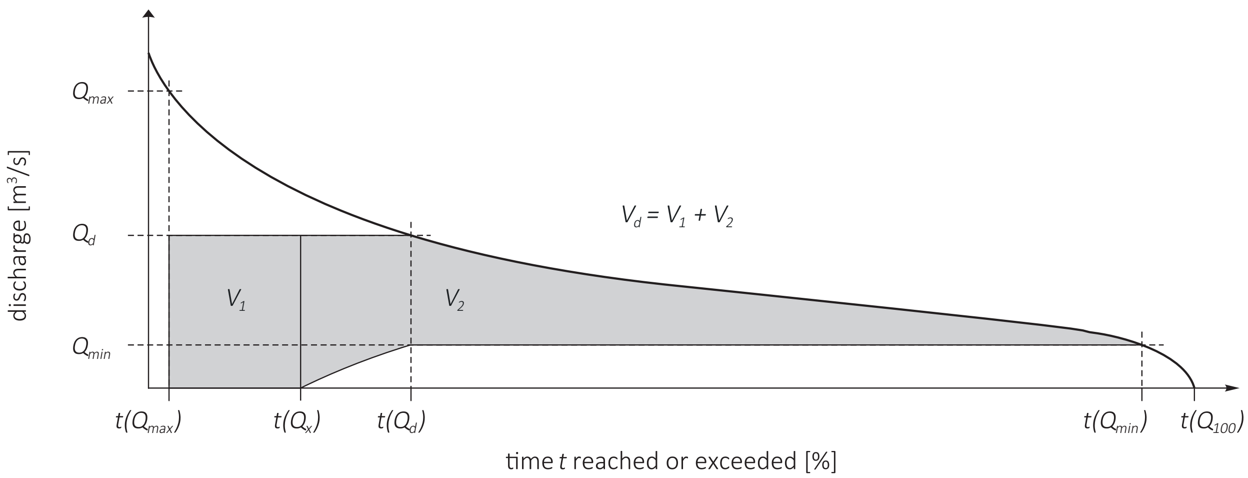


Fig. 11. Model flow duration curve (FDC), characterized by the parameters Q_d, Q_{min} and Q_{max} (HÄNGGI and WEINGARTNER 2012: 1238).

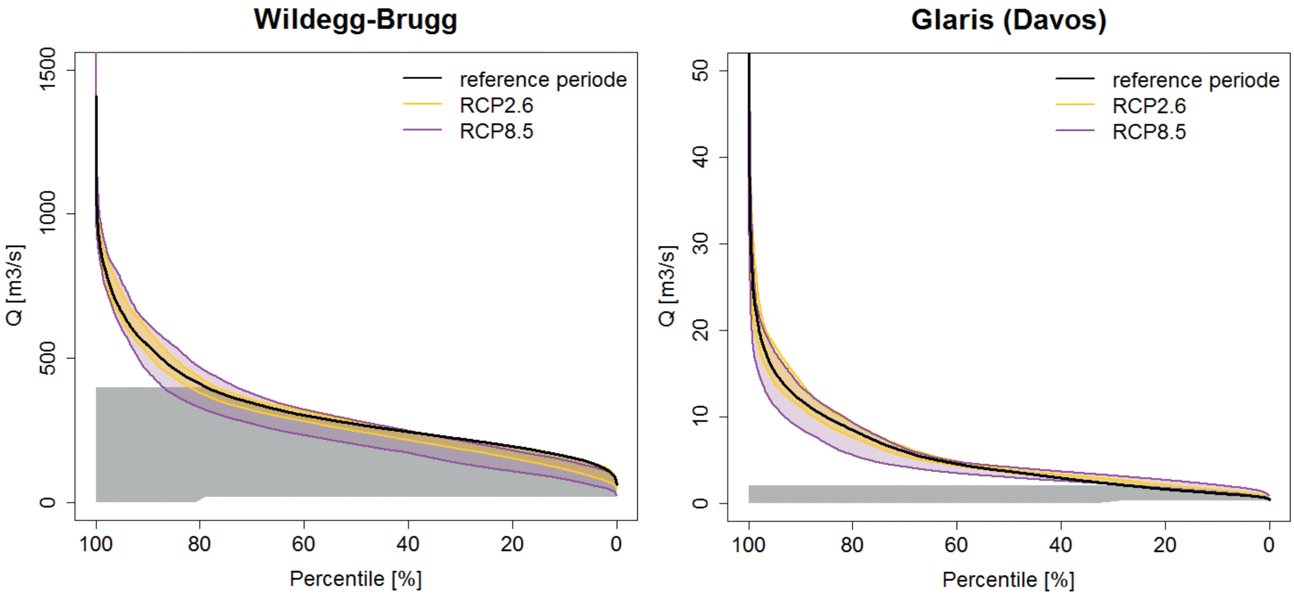


Fig. 12. Flow duration curves (FDCs) for the RoR power plants Wildegg-Brugg (Aare; left) and Glaris (Landwasser; right). The black line represents the reference period (1981–2010), the grey shaded area represents the usable water volume, and the areas bounded by yellow curves and purple curves represent the range of FDCs for the projected RCP2.6 and RCP8.5 emissions scenarios, respectively, for the end of the century.

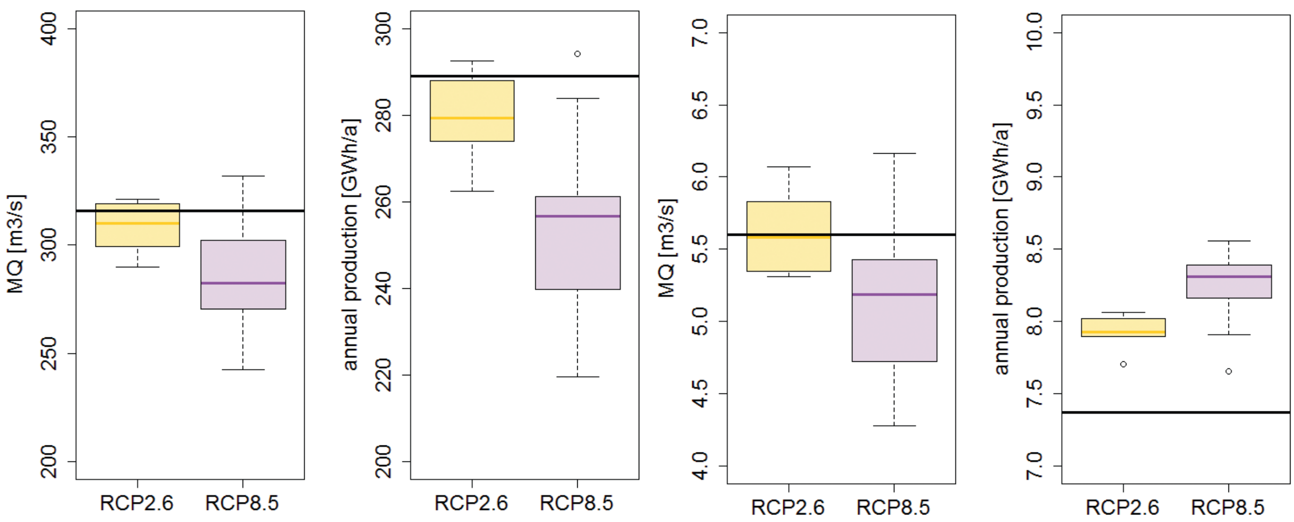


Fig. 13. The expected changes in the annual mean discharge [MQ] and mean production [GWh/a] at the Wildegg-Brugg power station (left) and at the Glaris power station (right) for the end of the century. The black line indicates the median value of the reference period. The yellow (RCP2.6) and purple (RCP8.5) boxplots represent the range of the different model chains.

to increase under the future scenarios. The right panel shows values for the Glaris (Davos) RoR power plant along the Landwasser, an Alpine river. Here, the number of days with low flow will decrease because of more winter precipitation.

The water volume usable for HP production (shaded area in Fig. 12) depends mainly on low and medium water ranges. For the RoR power plant Wildegg-Brugg, the hydrological predictions indicate that both the average water supply and the annual production will decrease in the future (Fig. 13, left). The majority of changes to the water supply are in the low water range that is important for HP production.

For the RoR power plant Glaris, which is heavily influenced by snowmelt, the total water supply will slightly decline by the end of the century; still, HP production is likely to increase (Fig. 13, right). The low water range supply will tend to increase as a result of the modified regime, which is favourable for that specific power plant dimension.

Importance for Hydropower

Figure 14 shows the FDC analyses of 11 RoR power plants on a map and how annual production (left) and winter production (right) are expected to change by mid-century and the end of the century compared to 1981–2010.

By mid-century (2045–2074):

– Annual production will remain roughly the same with concerted mitigation efforts (RCP2.6) as during the reference period. Production will decrease slightly (about 3 %) without climate change mitigation (RCP8.5). Exceptions are power plants that are influenced by strong melting processes.
– Winter production will increase at almost every RoR power plant considered in this study by mid-century, by about 5 % on average.

By the end of the century (2070–2099):

– Annual production will decline slightly (1.5 %) with concerted mitigation efforts (RCP2.6). Without climate change mitigation (RCP8.5), production will fall further (7 %).
– Winter production will increase at virtually all of the RoR power plants in this study. Depending on the emissions scenario, the average change will be between 5 % (RCP2.6) and 10 % (RCP8.5). However, the increase in winter production will not be sufficient to keep annual production from declining.

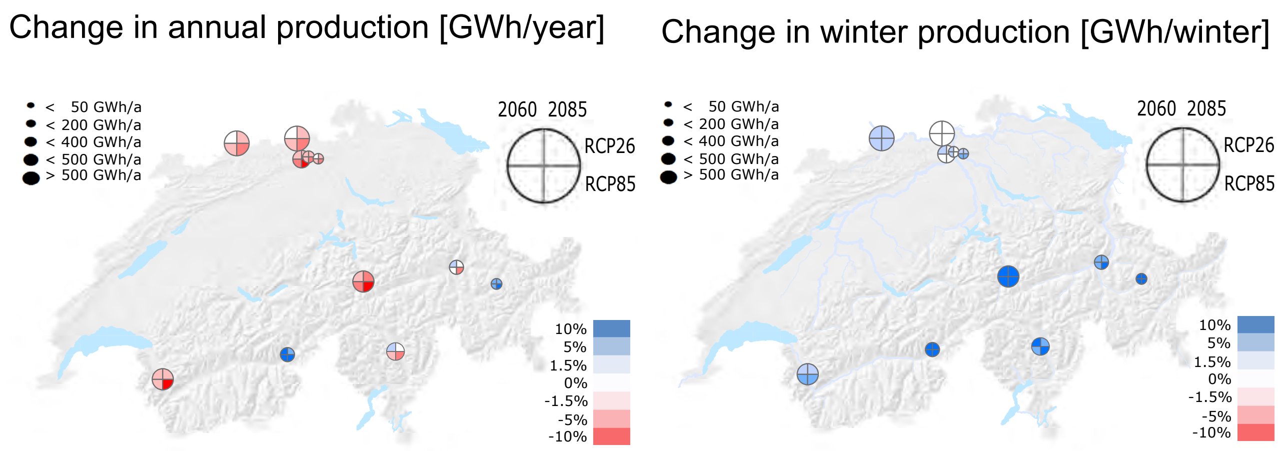


Fig. 14. Expected changes in annual (left) and winter (right) production of selected Swiss run-of-river power plants for the periods 2060 (mid-century, 2045–2074) and 2085 (end of century, 2070–2099). The calculations are based on the most recent Climate Change Scenarios CH2018 established by MeteoSwiss (21 climate models; two emission scenarios: with concerted mitigation efforts RCP2.6 and no climate change mitigation RCP8.5) and a state-of-the-art hydrological model (PREVAH), taking into account unchanged installed machinery and residual water flow requirements.

Tab. 1. Annual RoR power production and projected change for the periods 2060 and 2085 under the emissions scenarios RCP2.6 and RCP8.5 sorted by water intake elevation [m a.s.l.].

Annual production			**GWh/Year**	**Change [%] 2060**		**Change [%] 2085**	
Name	**[m a.s.l.]**	**River**	**Reference**	**RCP2.6**	**RCP8.5**	**RCP2.6**	**RCP8.5**
Birsfelden	265	Rhein	557.8	−1 %	−4 %	−1 %	−8 %
Albbruck-Dogern	318	Rhein	581.4	−1 %	−4 %	−2 %	−8 %
Windisch	337	Reuss	12.3	−1 %	−3 %	−2 %	−6 %
Aue	359	Limmat	27.8	−1 %	−4 %	−2 %	−10 %
Wildegg-Brugg	361	Aare	289.2	−3 %	−6 %	−3 %	−11 %
Lavey	451	Rhone	412.1	−2 %	−4 %	−2 %	−11 %
Reichenau	596	Rhein	111.6	2 %	0 %	1 %	−6 %
Biaschina	618	Ticino	360.6	4 %	−5 %	1 %	−8 %
Amsteg	815	Reuss	461.7	−4 %	−6 %	−7 %	−12 %
Aletsch	1444	Massa	183.2	11 %	19 %	10 %	24 %
Glaris	1473	Landwasser	7.5	7 %	8 %	5 %	11 %
Year			**Reference**	**2060**		**2085**	
RCP2.6			3004 GWh	2994 GWh (−0.3 %)		2963 GWh (−1.4 %)	
RCP8.5				2916 GWh (−2.9 %)		2787 GWh (−7.2 %)	

Tab. 2. Winter RoR power production and projected change for the periods 2060 and 2085 under the emissions scenarios RCP2.6 and RCP8.5 sorted by water intake elevation [m a.s.l.].

Winter production			**GWh/Winter**	**Change [%] 2060**		**Change [%] 2085**	
Name	**[m a.s.l.]**	**River**	**Reference**	**RCP2.6**	**RCP8.5**	**RCP2.6**	**RCP8.5**
Birsfelden	265	Rhein	239.6	2 %	3 %	2 %	2 %
Albbruck-Dogern	318	Rhein	276.1	1 %	1 %	1 %	0 %
Windisch	337	Reuss	5.9	2 %	2 %	0 %	0 %
Aue	359	Limmat	12.3	3 %	6 %	3 %	7 %
Wildegg-Brugg	361	Aare	138.6	1 %	0 %	1 %	−1 %
Lavey	451	Rhone	174.3	4 %	6 %	2 %	6 %
Reichenau	596	Rhein	45.7	8 %	8 %	5 %	12 %
Biaschina	618	Ticino	133.3	13 %	9 %	8 %	18 %
Amsteg	815	Reuss	134.7	19 %	33 %	14 %	54 %
Aletsch	1444	Massa	53.3	24 %	42 %	20 %	63 %
Glaris	1473	Landwasser	3.2	13 %	16 %	13 %	25 %
Winter			**Reference**	**2060**		**2085**	
RCP2.6			1217 GWh	1295 GWh (+6.4 %)		1274 GWh (+4.7 %)	
RCP8.5				1320 GWh (+8.4 %)		1367 GWh (+12.3 %)	

7 Adaptations

The previous sections have demonstrated that climate change will have manifold effects on hydropower (HP) production. At the same time, there is a national interest to increase electricity generation in an environmentally sustainable way. Options for adaptation are at hand through technical, conceptual, strategic and social measures. The challenge lies in making sensible adjustments to minimize future deficits and risks for the ecosystem and other water users.

Glaciers and snow

With the retreat of glaciers and the decline of snow cover in the Alps, the water supply for filling HP reservoirs and producing HP in summer will diminish. Reservoirs in deglaciated areas is an option to partly substitute the function of glaciers and snow cover as seasonal water storage (Fig. 15). Farinotti *et al.* (2016) estimated that for the European Alps, replacing glaciers with new dams could offset up to 65% of the expected summer runoff changes from presently glacierized surfaces. An increase in seasonal water storage capacity can also result from dam heightening in existing reservoirs, off-stream storage, reservoir interconnection or new reservoirs in periglacial areas (Guittet *et al.* 2016).

- **In the future, reservoirs in periglacial areas could partly substitute the storage function of glaciers.**
- **Technical or operational adjustments are necessary to mitigate the negative impacts of sediments on water ecology and HP production.**

Sediments

Today's sediment management in the context of HP deals with the sedimentation of reservoirs, the sustainable sediment regulation at intakes and the adherence of the Federal Act on the Protection of Waters. To cope with the climate-change-induced modification of sediment delivery to HP plants, there are various countermeasures to reduce sediment input and to increase sediment output from a reservoir:

– ***Consideration of impact loads on fine sediment to prevent damage***

Provided that the regulatory framework and production obligations allow, it may be advantageous to close the water extraction and interrupt turbine operation during periods of high sediment load. These measures would prevent damage and thus avoid consequential costs of almost 3% of the usual annual revenue (Felix 2017).

– **Fine sediment release from reservoirs through venting of turbidity currents**

A recent study examined an innovative system called SEDMIX, which allows fine particles near the outlets and dam to be kept suspended or resuspended by specific water jet arrangements, consequently avoiding reservoir silting (Fig. 16). The evacuation rate, i.e. the

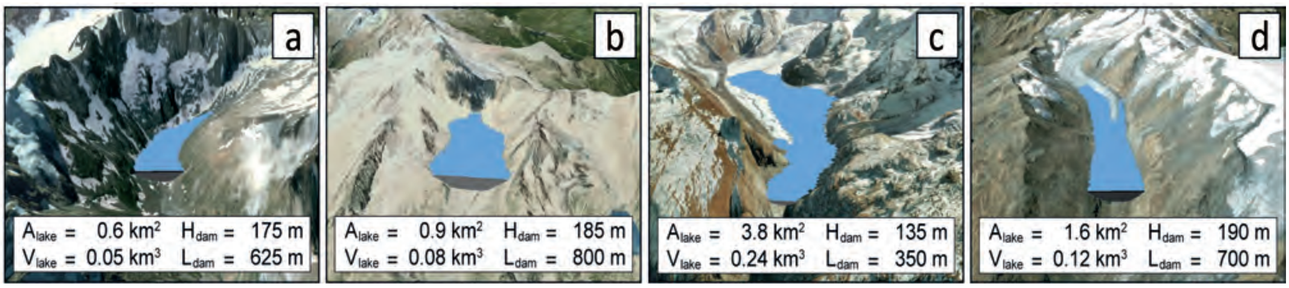


Fig. 15. Four hypothetical reservoirs are visualized for examples in the (a) French, (b) Italian, (c) Swiss, and (d) Austrian Alps. For each example, the area (A_{lake}) and volume (V_{lake}) of the generated lake, as well as the maximal height (H_{dam}) and the length of the crest of the required dam (L_{dam}), are given (for comparison: Grande Dixence, the largest dam currently installed in the European Alps, has A_{lake} = 3.7 km^2, V_{lake} = 0.40 km^3, H_{dam} = 285 m, L_{dam} = 700 m). Topographical imagery is from GoogleTM Earth (Farinotti 2016: 7).

rate of sediment transport downstream, was found to be increased by up to 70 % by venting the turbidity flows (AMINI *et al.* 2017).

– ***Fine sediment management at hydropower schemes considering turbine erosion***

Occasional sediment release at the dam toe, as typically occurs during purging operations, leads to a temporarily high concentration of suspended sediment, which can have negative impacts on downstream ecology and habitats. Another way of reducing reservoir sedimentation and avoiding such high suspended sediment concentrations is to increase the transport of fine sediment through the power waterway. As a result, sediment-induced costs increase due to erosion of hydraulic machinery. The optimal suspended sediment concentration in the turbine water results from an economic trade-off between these costs and the value of the avoided or restored active storage capacity (FELIX *et al.* 2017).

– ***Sediment management from an operational and ecological point of view***

With regard to sediment delivery, residual flow is not always sufficient. Residual flow in such a system reduces water availability for HP production. If residual flow does not improve ecological functioning, as sediment load is not taken into account, the situation can be described as a lose-lose solution. Suitable sediment management must be seen as an integral part of the design of ecological currents in abstraction systems and should take into account the different conditions of dams and water intakes to find a win-win solution (GABBUD and LANE 2016).

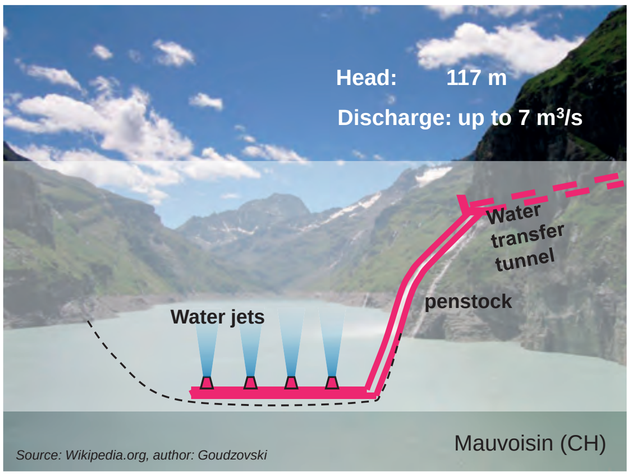


Fig. 16. Illustration of the SEDMIX concept, applied to the Corbassière water transfer tunnel to the Mauvoisin dam (JENZER-ALTHAUS *et al.* 2011: 106).

Natural hazards

Proglacial lakes can produce sudden water release with potentially catastrophic consequences (FREY *et al.* 2010; WORNI *et al.* 2014; HAEBERLI *et al.* 2016). In this context, early planning and hazard prevention measures, such as lake-level lowering and flood retention, will become necessary in the future (FREY *et al.* 2010; NELAK 2013; HAEBERLI *et al.* 2016). Reservoir management might need adjustment to keep volumes free for anticipated high flows or to reduce risk in the case of landslides and avalanches. Furthermore, spillways and outlet works play a fundamental role in dam safety. For existing and planned reservoirs, the risk of dam overtopping by landslide-generated waves plays a crucial role in dam safety assessment (FUCHS and BOES 2016; EVERS *et al.* 2018). They must ensure a certain discharge in the face of the arrival of a flood with a certain volume. Large wood transport must thereby be taken into account to avoid blocking of the spillway intake (BOES and SCHMOCKER 2019).

- **Dams can be at risk or be a risk themselves, and they can lower hydrological risks related to climate change; these three dimensions of risks need to be re-evaluated under climate change.**
- **Multipurpose operating strategies for HP systems are required to ensure HP generation, reliability and flexibility of supply, operational profitability, and ecosystem conservation under conditions of more fluctuating demand.**

Competing water use

In order to optimize Swiss HP plants for the future, both physical and operational adaptations must be taken into account. In addition to handling the task of generating electricity, today's water management must also deal with the effects of climate change, operational safety of buildings with regard to (new) natural hazards, sediment transport and reservoir sedimentation, protection of ecosystems, and socio-economic requirements. Through new technological adaptations, existing infrastructures should increase their efficiency of production and achieve higher operation flexibility during seasonal and daily peak demands. To fill the gap (deficit), investments (construction of new plants) in areas where there is still untapped potential could be considered to counter the effects of climate change on electricity generation. In other areas where the potential is almost exhausted, better technologies (e. g. higher efficiency) for existing systems would help mitigate the effects or increase the

Fig. 17. Visualization of heightening the Sambuco dam by 10 m (during construction) (SCCER-SoE 2018: 74).

contribution of HP to electricity generation (Hamadudu 2012). Increasing the efficiency of existing HP plants and reservoirs through their expansion enables more flexible operation with new and strongly fluctuating demand. A systematic investigation of dam heightening (Fig. 17) at 25 Swiss dams demonstrated that this adjustment would enable an additional 2.3 TWh/a of stored energy which might be transfered from the summer to the winter half year (Fuchs *et al.* 2019; Boes 2019), corresponding to about 25% of today's total energy stored in Swiss reservoirs.

Swiss HP plants already play an important role in the supply of peak energy in the European grid and thus contribute to the balancing of the volatile production of renewable electricity. HP plants will remain important players not only for power production, but also increasingly for further services, most importantly the prevention of climate change related hazards and the storage of surplus water for other purposes (substituting glaciers and snow cover). New operation strategies are needed to determine future forecast requirements, especially for multipurpose reservoirs (Schaefli 2015). New strategies for HP systems are necessary to meet the needs of power generation, reliability and flexibility of supply, operational profitability, and ecosystem protection under conditions of more fluctuating demand. These requirements will be an essential part of the renewal of the concession and the question of which functions can be supported by HP plants (Manso *et al.* 2015).

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References

Addor, N.; Rössler, O.; Köplin, N.; Huss, M.; Weingartner, R.; Seibert, J., 2014: Robust changes and sources of uncertainty in the projected hydrological regimes of Swiss catchments. Water Resources Research, 50, 7541–7562.

Amini, A.; Manso, P.A.; Venuleo, S.; Lindsay, N.; Leupi, C.; Schleiss, A.J., 2017: Computational hydraulic modelling of fine sediment stirring and evacuation through the power waterways at the Trift reservoir. At: Conference Hydro 2017, Seville.

Ayala, A.; Farinotti, D.; Bavay, M.; Marty, C.; Huss, M.; Stoffel, M., 2020, in publication: Glaciers. Hydro-CH2018 synthesis report chapters: Future Changes in Hydrology. Hydro-CH2018 Project. Federal Office for the Environment (FOEN), Bern, Switzerland.

Bakker, M.; Costa A.; Silva T.A.; Stutenbecker, L.; Girardclos, S.; Loizeau, J.L.; Molnar, P.; Schlunegger, F.; Lane, S.N., 2017: Combined Flow Abstraction and Climate Change Impacts on an Aggrading Alpine River. Water Resources Research, 54, Issue 1, 223–242.

Beniston, M., 1997: Variation of snow depth and duration in the Swiss Alps over the last 50 years: Links to changes in large-scale climatic forcings. Climate Change, 36, 281–300.

Beniston, M., 2012: Exploring the behavior of atmospheric temperatures under dry conditions in Europe: evolution since the mid-20th century and projections for the end of the 21st century. International Journal of Climatology, 33, Issue 2, 457–462.

Beniston, M.; Stoffel, M., 2016: Rain-on-snow events, floods and climate change in the Alps: Events may increase for warming up to 4°C and decrease thereafter. Science of the Total Environment, 571, 228–236.

Beniston, M.; Stoffel, M.; Hill, M., 2011: Impacts of climatic change on water and natural hazards in the Alps: Can current water governance cope with future challenges? Examples from the European 'ACQWA' project. Environmental Science and Policy, 14, 734–743.

Bennett, G.; Molnar, P.; Eisenbeiss, H.; McArdell, B.W., 2012: Erosional power in the Swiss Alps: characterization of slope failure in the Illgraben. Earth Surface Processes and Landforms, 37, Issue 15, 1627–1640.

Blöschl, G.; Hall, J.; Parajka, J.; Perdigão, R.A.P.; Merz, B.; Arheimer, B.; Aronica, G.T.; Bilibashi, A.; Bonacci, O.; Borga, M.; Canjevac, I.; Castellarin, A.; Chirico, G. B.; Claps, P.; Fiala, K.; Frolova, N.; Gorbachova, L.; Gül, A.; Hannaford, J.; Harrigan, S.; Kireeva, M.; Kiss, A.; Kjeldsen, T.R.; Kohnová, S.; Koskela, J.J.; Ledvinka, O.; Macdonald, N.; Mavrova-Guirguinova, M.; Mediero, L.; Merz, R.; Molnar, P.; Montanari, A.; Murphy, C.; Osuch, M.; Ovcharuk, V.; Radevski, I.; Rogger, M.; Salinas, J.L.; Sauquet, E.; Šraj, M.; Szolgay, J.; Viglione, A.; Volpi, E.; Wilson, D.; Zaimi, K.; Živkovic, N., 2017: Changing climate shifts timing of European floods. Science, 357, Issue 6351, 588–590.

Boes, R., 2019: Schweizerisches Speicherwasserkraftpotential durch Aus- und Neubauten unter Berücksichtigung von technischer Machbarkeit und Nachhaltigkeitskriterien. At: Fachtagung Wasserkraft des Verbands Schweizerischer Elektrizitätsunternehmen, Olten, 22.08.2019.

Boes, R.; Delaney, I.; Ehrbar, D.; Farinotti, D.; Schmocker, L.; Vetsch, D.; Werder, M., 2020: in press: Stauseen, wo früher Gletscher waren? NRP70 synthesis report, Swiss National Science Foundation, Bern, Switzerland.

Boes, R.; Schmocker, L., 2019: Umgang mit Schwemmgut an Talsperren ('Handling of floating debris at dam reservoirs'). WasserWirtschaft, 109, Issue 5, 162–165.

Boroneant, C.; Plaut, G.; Giorgi, F.; Bi, X., 2006: Extreme precipitation over the Maritime Alps and associated weather regimes simulated by a regional climate model: Present-day and future climate scenarios. Theoretical and Applied Climatology, 86, 81–99.

Brunner, M.; Björnsen Gurung, A.; Zappa, M.; Zekollari, H.; Farinotti, D.; Stähli, M., 2019: Present and future water scarcity in Switzerland: Potential for alleviation through reservoirs and lakes. Elsevier, 666, 1033–1047.

CH2018, 2018: CH2018 – Climate Scenarios for Switzerland, Technical Report, National Centre for Climate Services, Zurich, 271 pp. ISBN: 978-3-9525031-4-0.

Costa, A.; Molnar, P.; Stutenbecker, L.; Bakker, M.; Silva, T.A.; Schlunegger, F.; Lane, S.N.; Loizeau, J.L.; Girardclos, S., 2018: Temperature signal in suspended sediment export from an Alpine catchment. Hydrology and Earth System Sciences, 1–30.

Durand, Y.; Giraud, G.; Laternser, M.; Etchevers, P.; Merindol, L.; Lesaffre, B., 2009: Reanalysis of 47 Years of Climate in the French Alps, (19582005: Climatology and Trends for Snow Cover. Journal of Applied Meteorology and Climatology, 48, 2487–2512.

Ehrbar, D.; Schmocker, L.; Vetsch, D.F.; Boes, R.M., 2018: Hydropower Potential in the Periglacial Environment of Switzerland under Climate Change. Sustainability, 10, 2794.

Evans, S.G.; Delaney, K.B., 2015: Catastrophic Mass Flows in the Mountain Glacial Environment. Snow and Ice-Related Hazards, Risks and Disasters, Elsevier, 563–606.

Evers, F.M.; Schmocker, L.; Fuchs, H.; Schwegler, B.; Fankhauser, A.U.; Boes, R.M., 2018: Landslide generated impulse waves: assessment and mitigation of hydraulic hazards. 26th Congress of the international Comission on Large Dams, Vienna, 679–694.

Farinotti, D.; Pistocchi, A.; Huss, M., 2016: From dwindling ice to headwater lakes: could dams replace glaciers in the European Alps? Environmental Research Letters 11, 054022.

Fatichi, S.; Rimkus, S.; Burlando, P.; Bordoy, R.; Molnar, P., 2013: Elevational dependence of climate change impacts on water resources in an Alpine catchment. Hydrology and Earth System Sciences Discussions, 10, 3743–3794.

Felix, D., 2017: Experimental investigation on suspended sediment, hydro-abrasive erosion and efficiency reductions of coated Pelton turbines. VAW-Mitteilungen 238, 8. Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW), (R.M. Boes, ed.), ETH Zürich, Schweiz.

Felix, D.; Albayrak, I.; Boes, R., 2017: Weiterleitung von Feinsedimenten via Triebwasser als Massnahme gegen die Stauraumverlandung. Wasser Energie Luft, 109, Issue 2, 85–90.

Fischer, M.; Huss, M.; Hoelzle, M., 2015: Surface elevation and mass changes of all Swiss glaciers 1980–2010. The Cryosphere 9, 525–540.

Frey, H.; Haeberli, W.; Linsbauer, A.; Huggel, C.; Paul, F., 2010: A multi-level strategy for anticipating future glacier lake formation and associated hazard potentials. Natural Hazards Earth System Sciences, 10, 339–352.

Fuchs, H.; Boes, R.M., 2016: Slide induced impulse waves in mountainous regions. 13th Congress Interpraevent – Living with natural risks, Lucerne, 265–273.

Fuchs, H.; Felix, D.; Müller-Hagmann, M.; Boes, R., 2019: Bewertung von Talsperren-Erhöhungsoptionen in der Schweiz ('Assessment of dam heightening options in Switzerland'). WasserWirtschaft, 109, Issue 5, 146–149.

Gabbud, C.; Lane, S.N., 2016: Ecosystem impacts of Alpine water intakes for hydropower: The challenge of sediment management. WIREs Water, 3, 41–61.

Genevois, R.; Prestininzi, A., 2013: International Conference on: Vajont – 1963–2013, Thoughts and analyses after 50 years since the catastrophic landslide. Padua, Journal of Engineering Geology and Environment.

Gruber, S.; Hoelzle, M.; Haeberli, W., 2004: Permafrost thaw and destabilization of Alpine rock walls in the hot summer of 2003. Geophysical Research Letters 31, L13504.

Guittet, M.; Capezzali, M.; Gaudard, L.; Romerio-Guidici, F.; Vuille, F.; Avellan, F., 2016: Study of the drivers and asset management of pumped-storage power plants historical and geographical perspective. Energy, 111, 560–579.

Haeberli, W.; Bütler, M.; Huggel, C.; Lehmann, T.; Schaub, Y.; Schleiss, A., 2016: New lakes in deglaciating high-mountain regions – opportunities and risks. Climatic Change, 139, 201–214.

Hamududu, B.; Killingtveit, A., 2012: Assessing climate change impacts on global hydropower. Energies, 5, 305–322.

Hänggi, P.; Weingartner, R., 2012: Variations in discharge volumes for hydropower generation in Switzerland. Water Resource Management 26, Issue 5, 1231–1252.

Horton, P.; Schaefli, B.; Mezghani, A.; Hingray, B.; Musy, A., 2006: Assessment of climate-change impacts on Alpine discharge regimes with climate model uncertainty. Hydrological Processes, 20, Issue 10, 2091–2109.

Huggel, C.; Clague, J.J.; Korup, O., 2012: Is climate change responsible for changing landslide activity in high mountains? Earth Surface Processes and Landforms, 37, 77–91.

Huggel, C.; Fischer, L.; Schneider, D., 2008: Gletscher- und Permafrost-Naturgefahren in der Perspektive sich ändernder Umweltbedingungen. Deutsche Gesellschaft für Geotechnik/Geowissenschaften, Fachsektion Ingenieurgeologie, Rundbrief 66, Sonderheft zur 18. Bodenseetagung der Deutschen, Oesterreischichen und Schweizerischen Fachgruppen der Ingenieurgeologie, 39–40.

Huss, M., 2011: Present and future contribution of glacier storage change to runoff from macroscale drainage basins in Europe. Water Resources Research 47, Issue 7, 1–14.

Huss, M.; Bookhagen, B.; Huggel, C.; Jacobsen, D.; Bradley, R.; Clague, J.; Vuille, M.; Buytaert, W.; Cayan, D.; Greenwood, G.; Mark, B.; Milner, A.; Weingartner, R.; Winder, M., 2017: Toward mountains without permanent snow and ice. Earth's Future, 5, Issue 5, 418–435.

Huss, M.; Hock, R., 2018: Global-scale hydrological response to future glacier mass loss. Nature climate change, 8, 135–140.

Jakob, M.; Lambert, S., 2009: Climate change effects on landslides along the southwest coast of British Columbia. Geomorphology, 107, 275–284.

Jenzer-Althaus, J.; De Cesare, G.; Schleiss, A., 2011: Entlandung von Stauseen über Triebwasserfassungen durch Aufwirbeln der Feinsedimente mit Wasserstrahlen. Wasser Energie Luft, 103, Issue 2, 105–112.

Josi, P., 2018: Wassermanagement in der technischen Beschneiung und Zukunftsvisionen des Schneesports in der Schweiz. Masterarbeit. Universität Bern.

Jossen, L.; Björnsen Gurung, A., 2018: Möglichkeiten und Grenzen von Mehrzweckspeichern in der Schweiz und ihr Beitrag zur regionalen Resilienz. Wasser Energie Luft, 110, Issue 2, 108–112.

Köplin, N.; Schädler, B.; Viviroli, D.; Weingartner, R., 2014: Seasonality and magnitude of floods in Switzerland under future climate change. Hydrological Processes, 28, Issue 4, 2567–2578.

Kummer, D., 2017: Charakterisierung der Verdunstungsverhältnisse in der Schweiz anhand repräsentierbarer Stationen. Masterarbeit. Universität Bern.
Lane, S.N.; Bakker, M.; Gabbud, C.; Micheletti, N.; Saugy, J.N., 2017: Sediment export, transient landscape response and catchment-scale connectivity following rapid climate warming and Alpine glacier recession. Geomorphology, 277, 210–227.
Langhammer, L.; Rabenstein, L.; Schmid, L.; Bauder, A.; Grab, M.; Schaer, P.; Maurer, H., 2019a: Glacier bed surveying with helicopter-borne dual-polarization ground-penetrating radar. Journal of Glaciology, 65, Issue 249, 123–135.
Langhammer, L.; Grab, M.; Bauder, A.; Maurer, H., 2019b: Glacier thickness estimations of alpine glaciers using data and modeling constraints, The Cryosphere, 13, 2189–2202.
Laternser, M.; Schneebeli, M., 2003: Long-term snow climate trends of the Swiss Alps (1931–99). International journal of climatology, 23, 733–750.
Malm, R., 2016: Guidelines for FE Analyses of Concrete Dams. Tech. rep.; Energiforsk.
Mangini, W.; Viglione, A.; Hall, J.; Hundecha, Y.; Ceola, S.; Montanari, A.; Rogger, M.; Salinas, J.L.; Borzì, I.; Parajka, J., 2018: Detection of trends in magnitude and frequency of flood peaks across Europe. Hydrological Sciences Journal, 63, Issue 4, 493–512.
Manso, P.; Schaefli, B.; Schleiss, A.J., 2015: Adaptation of Swiss hydropower infrastructure to meet future electricity needs. Hydro 2015, Advancing policy and practice. Bordeaux, 26–28 Oct. 2015: The International Journal on Hydropower and Dams.
Marty, C., 2008: Regime shift of snow days in Switzerland. Geophysical Research Letters, 35, L12501.
Marty, C.; Bavay, M.; Farinotti, D.; Ayala, A.; Huss, M.; Stoffel, M., 2020, in publication: Snow. Hydro-CH2018 synthesis report chapters: Future Changes in Hydrology. Hydro-CH2018 Project. Federal Office for the Environment (FOEN), Bern, Switzerland.
Marty, C.; Schlögl, S.; Bavay, M.; Lehning, M., 2017a: How much can we save? Impact of different emission scenarios on future snow cover in the Alps. The Cryosphere, 11, 517–529.
Marty, C.; Tilg, A.M.; Jonas, T., 2017b: Recent evidence of largescale receding snow water equivalents in the European Alps. Journal of Hydrometeorology, 18, 1021–1031.
Molnar, P.; Fatichi, S.; Gaál, L.; Szolgay, J.; Burlando, P., 2015: Storm type effects on super Clausius–Clapeyron scaling of intense rainstorm properties with air temperature. Hydrology and Earth System Sciences, 19, Issue 4, 1753.
Morris, G.L.; Fan, J., 1998: Reservoir Sedimentation Handbook. New York: McGraw-Hill.
NCCS, 2018: Klima Schweiz – Webatlas. https://www.nccs.admin.ch/nccs/de/home/materialien-und-daten/daten/ch2018-webatlas.html (June 2019).
NELAK, 2013: Neue Seen als Folge des Gletscherschwundes im Hochgebirge – Chancen und Risiken. Formation des nouveux lacs suite au recul des glaciers en haute montagne – chances et risques. Forschungsbericht NFP 61.
Haeberli, W.; Bütler, M.; Huggel, C.; Müller, H.; Schleiss A. (Hrsg.). Zürich, vdf Hochschulverlag AG an der ETH Zürich.
Peleg, N.; Fatichi, S.; Paschalis, A.; Molnar, P.; Burlando, P., 2017: An advanced stochastic weather generator for simulating 2-D high-resolution climate variables. Journal of Advances in Modeling Earth Systems, 9, Issue 3, 1595–1627.
Peleg, N.; Molnar, P.; Burlando, P.; Fatichi, S., 2019: Exploring stochastic climate uncertainty in space and time using a gridded hourly weather generator. Journal of Hydrology, 571, 627–641.
Pfister, C., 2009: Learning from nature-induced disasters. Theoretical considerations and case studies from Western Europe. In: Natural disasters, cultural responses. Case studies toward a global environmental history. Herausgegeben von C.; Mauch, C.; Pfister, Lanham, M.D.: Lexington Books, 17–40.
Pielmeier, C.; Techel, F.; Marty, C.; Stucki, T., 2013: Wet snow avalanche activity in the Swiss Alps – trend analysis for midwinter season. International Snow Science Workshop, Grenoble, 07–11 October 2013, 1240–1246.
Quinton, W.L.; Carey, S.K., 2008: Towards an energy-based runoff generation theory for tundra landscapes. Hydrological Processes, 22, 4649–4653.
Raymond-Pralong, M.; Turowski, J.; Rickenmann, D.; Zappa, M., 2015: Climate change impacts on bedload transport in Alpine drainage basins with hydropower exploitation. Earth Surface Processes and Landforms, 40, 1587–1599.
Savelsberg, J.; Schillinger, M.; Schlecht, I.; Weigt, H., 2018: The Impact of Climate Change on Swiss Hydropower. Sustainability, 10, 2541.
SCCER-SoE, 2018: Science Report. Swiss Competence Center for Energy Research – Supply of Electricity (SCCER-SoE).
Schaefli, B., 2015: Projecting hydropower production under future climates: A guide for decision-makers and modelers to interpret and design climate change impact assessments. WIREs Water, 2, 271–89.
Schaefli, B.; Hingray, B.; Musy, A., 2007: Climate change and hydropower production in the Swiss Alps: quantification of potential impacts and related modelling uncertainties. Hydrology and Earth System Sciences, 11, 1191–1205.
Schaefli, B.; Manso, P.; Fischer, M.; Huss, M.; Farinotti, D., 2019: The role of glacier retreat for Swiss hydropower production. Renewable Energy, 132, 615–627.
Scherrer, S.C.; Appenzeller, C., 2006: Swiss Alpine snow pack variability: major patterns and links to local climate and large-scale flow. Climate Research, 32, 187–199.

SCHERRER, S.C.; APPENZELLER, C.; LATERNSER, M., 2004: Trends in Swiss Alpine snow days: the role of local- and large-scale climate variability. Geophysical Research Letters 31, L13215.

SCHLEISS, A.; DE CESARE, G.; JENZER ALTHAUS, J., 2010: Verlandung der Stauseen gefährdet die nachhaltige Nutzung der Wasserkraft ('Reservoir sedimentation threatens the sustainable use of hydropower'). Wasser Energie Luft, 102, 31–40.

SCHLEISS, A.; FEUZ, B.; AEMMER, M.; ZUND, B., 1996: Problems of reservoir sedimentation in the lake Mauvoisin, extent, effect and possible measures. In Sedimentation in Reservoirs and Related Problems. Water Mains and Canals, VAW Mitteilung, 142, 37–58.

SCHNEIDER, D.; HUGGEL, C.; HAEBERLI, W.; KAITNA, R., 2011: Unraveling driving factors for large rock-ice avalanche mobility. Earth Surface, Processes and Landforms, 36, Issue 14, 1948–1966.

SCHNEUWLY, D.M.; STOFFEL, M., 2008: Tree-ring based reconstruction of the seasonal timing, major events and origin of rockfall on a case-study slope in the Swiss Alps. Natural Hazards and Earth System Sciences, 8, 203–211.

SFOE, 2017: Statistics of the Swiss hydropower facilities – Statistik der Wasserkraftanlagen der Schweiz (WASTA). State 01.01.2017, available on http://www.bfe.admin.ch/geoinformation/05061/05249/index.html?lang=deand dossier_id=01049 (last accessed 09 July 2018). Bern, Swiss Federal Office for Energy.

SGHL, 2011: Auswirkungen der Klimaänderung auf die Wasserkraftnutzung – Synthesebericht. Schweizerische Gesellschaft für Hydrologie und Limnologie und Hydrologische Kommission. Beiträge zur Hydrologie der Schweiz.

SPREAFICO, M.; WEINGARTNER, R., 2005: Hydrologie der Schweiz – Ausgewählte Aspekte und Resultate. Berichte des BWG, Serie Wasser Nr. 7, Bern.

STOFFEL, M.; BENISTON, M., 2006: On the incidence of debris flows from the early Little Ice Age to a future greenhouse climate: a case study from the Swiss Alps. Geophysical Research Letters 33, L16404.

STOFFEL M.; HUGGEL, C., 2012: Effects of climate change on mass movements in mountain environments. Progress in Physical Geography, 36, 421–439.

STOFFEL, M.; LIÈVRE, I.; MONBARON, M.; PERRET, S., 2005a: Seasonal timing of rockfall activity on a forested slope at Täschgufer (Valais, Swiss Alps) – a dendrochronological approach. Zeitschrift für Geomorphologie, 49, 89–106.

STAFFLER, H.; POLLINGER, R.; ZISCHG, A.; MANI, P., 2008: Spatial variability and potential impacts of climate change on flood and debris flow hazard zone mapping and implications for risk management. Natural Hazards and Earth System Sciences, 8, 539–558.

STOFFEL, M.; SCHNEUWLY, D.; BOLLSCHWEILER, M.; LIÈVRE, I.; DELALOYE, R.; MYINT, M.; MONBARON, M., 2005b: Analyzing rockfall activity (1600–2002) in a protection forest—a case study using dendrogeomorphology. Geomorphology, 68, 224–241.

STOFFEL, M.; TIRANTI, D.; HUGGEL, C., 2014: Climate change impacts on mass movements – case studies from the European Alps. Science of the Total Environment, 493, 1255–1266.

STAHL, K.; WEILER, M.; FREUDIGER, D.; KOHN, I.; SEIBERT, J.; VIS, M.; GERLINGER, K.; BÖHM, M., 2016: Abflussanteile aus Schnee- und Gletscherschmelze im Rhein und seinen Zuflüssen vor dem Hintergrund des Klimawandels. Abschlussbericht an die Internationale Kommission für die Hydrologie des Rheingebietes - Enderfassung 08/2016, Bericht CHR 00-2016.

TERZAGO, S.; FRATIANNI, S.; CREMONINI, R., 2013: Winter precipitation in Western Italian Alps (1926–2010). Meteorology and Atmospheric Physics, 119, 125–136.

TUROWSKI, J.M.; YAGER, E.M.; BADOUX, A.; RICKENMANN, D., 2011: Start and end of bedload transport in gravel-bed streams. Geophysical Research Letters 38, L04401.

VIVIROLI, D.; ZAPPA, M.; GURTZ, J.; WEINGARTNER, R., 2009: An introduction to the hydrological modelling system PREVAH and its pre- and post-processing-tools. Environmental Modelling and Software, 24, Issue 10, 1209–1222.

WAN, C.F.; FELL, R., 2004: Investigation of Rate of Erosion of Soils in Embankment Dams. Journal of Geotechnical and Geoenvironmental Engineering, 130, 373–380.

WEHREN, B.; WEINGARTNER, R.; SCHÄDLER, B.; VIVIROLI, D., 2010: General characteristics of Alpine waters. Handbook of Environmental Chemistry, 6, Springer–Verlag: Berlin, Heidelberg, 17–58.

WEINGARTNER, R.; BARBEN, M.; SPREAFICO, M., 2003: Floods in mountain areas—an overview based on examples from Switzerland. Journal of Hydrology, 282, 10–24.

WORNI, R.; HUGGEL, C.; CLAGUE, J.; SCHAUB, Y.; STOFFEL, M., 2014: Coupling glacial lake impact, dam breach, and flood processes: a modeling perspective. Geomorphology, 224, 161–176.

WÜRZER, S.; WEVER, N.; JURAS, R.; LEHNING, M.; JONAS, T., 2017: Modelling liquid water transport in snow under rain-on-snow conditions – considering preferential flow. Hydrology and Earth System Sciences, 21, Issue 3, 1741–1756.

ZEKOLLARI, H.; HUSS, M.; FARINOTTI, D., 2019: Modelling the future evolution of glaciers in the European Alps under the EURO-CORDEX RCM ensemble. The Cryosphere, 13, 1125–1146.

Address

Swiss Competence Center for
Energy Research – Supply of Electricity
(SCCER-SoE)
ETH Zurich
Sonneggstrasse 5
8092 Zurich

www.sccer-soe.ch

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