Low Flow Events

A REVIEW IN THE CONTEXT OF CLIMATE CHANGE IN SWITZERLAND

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Executive Summary

Low flows are a normal phenomenon in the seasonal climate of Switzerland and ecosystems and water uses are adapted to their occurrence. Nevertheless, prolonged low flow events may present a number of challenges to water management, as experienced, for instance, in the drought and heat summer of 2003 and more recently in 2018. This report summarises the knowledge on climate change impacts on low flows and elaborates knowledge gaps.

In Switzerland there are clear regions with summer or winter low flows. This seasonality is related to the respective hydrological regimes. The primary consensus of trend analyses and climate change impact modelling studies is that annual winter low flow levels increase due to increases in winter precipitation, increasing temperatures, and less stable snowpacks. Hydropower reservoir management adds a quantitatively unclear component to this change. The development of summer low flows is far more complex with several processes and factors that may alleviate or aggravate low flow conditions. Overall trend signals in observed streamflow with respect to summer low flows are heterogeneous, but for lower elevation catchments some decreases have been demonstrated. Focused low flow analyses with current data, however, are lacking. The published studies are based mostly on periods that ended before the year 2010 and discussed mainly changes of seasonal flow and regime shifts. Some investigations of long-term records and reconstructions for events in the pre-instrumental period suggest that low flow events in the recent past, such as the event in 2003, did not match the extreme magnitude of earlier events such as those of 1921, 1947, or 1540. Climate scenario-led impact modelling studies for Swiss catchments largely agree on a general decrease of summer streamflow in the future. It is commonly assumed that these projected seasonal changes imply a higher risk of extreme summer low flows. However, modelling efforts with a targeted exploration of projected low flow extremes have been limited. They suffer from uncertainty, mainly due to limitations in the representation of dry extremes in climate models, the influence of downscaling techniques on temporal sequencing and other interdependencies, and limitations of the hydrological models and calibration strategies to capture extreme low flow conditions and processes. Comprehensive studies on these different uncertainty sources specifically for future low flows are necessary.

The cross-seasonal influence of winter snowpack and spring snowmelt on summer low flow is an emerging research topic and a particular challenge in the process understanding and climate change attribution. Due to the wet summer climate, a direct influence of long-term changes in winter snow characteristics on the developments of summer low flow events is difficult to detect in Switzerland. A better understanding, how changed snowmelt dynamics may affect groundwater recharge and discharge processes apart from shifted timing is needed. To achieve this, a better characterisation and formal description of the various catchment storages is necessary, requiring more detailed hydrogeological information not only for unconsolidated quaternary deposits but also for bedrock units. A coordinated monitoring of all water balance components alongside with information on river flow regulation and other human influences that may weigh more heavily in times of low flow is needed. Monitoring also needs to overcome common challenges in measuring error and uncertainty during very low flows. In light of the many difficulties of modelling efforts to project hydrological responses to future extreme events, scientists propose a shift to more efforts into bottom-up vulnerability approaches including stress-test scenarios or storyline simulations in parallel and as a complement to climate scenario-led model projections.

Zusammenfassung

Niedrigwasserphasen sind im Schweizer Klima ein normales Phänomen, an das Ökosysteme und Wassernutzung weitgehend angepasst sind. Dennoch können langanhaltende Niedrigwassersituationen mit zahlreichen Herausforderungen für die Wasserbewirtschaftung einhergehen, wie Erfahrungen im Trocken- und Hitzesommer 2003 oder auch jüngst im Jahr 2018 zeigten. Dieser Bericht fasst den Stand der Forschung und entsprechende Wissenslücken zu Auswirkungen des Klimawandels auf Niedrigwasserereignisse zusammen.

Gesteuert vom hydrologischen Regime, liegen in der Schweiz klare regionale Muster hinsichtlich der Saisonalität von Niedrigwasser mit generellem Auftreten im Sommer oder Winter vor. Sowohl Trendanalysen als auch Klimafolgenmodellierungen lassen auf zunehmende Winterabflüsse infolge zunehmender Wintertemperaturen und -niederschläge, damit geringer ausgeprägter Schneebedeckung und somit auch einer generell abnehmenden Relevanz von Winterniedrigwasser schließen. Auch die Stauseenbewirtschaftung trägt zur Tendenz erhöhter Winterabflüsse bei, jedoch in schwer näher quantifizierbarem Maß. Die Entstehung extremer Sommerereignisse ist durch eine Vielzahl von Prozessen und Faktoren, die die Niedrigwasserbedingungen verschärfen oder abmildern können, kompliziert. Vorliegende Trendstudien zu klimabedingten Veränderungen von Sommerniedrigwasserabflüssen stellten bei einigen der tiefergelegenen Gebiete abnehmende Tendenzen fest, erlauben jedoch insgesamt keine eindeutigen Aussagen. Gezielte Trendanalysen für Niedrigwasser anhand von Zeitreihen mit aktuellen Daten gibt es kaum. Die meisten Studien stützen sich auf vor 2010 endende Datenreihen und betrachten und diskutieren eher saisonale Abflüsse und Regimeänderungen. Im langzeitlichen Kontext erreichten Sommerereignisse der jüngeren Vergangenheit, wie das im Jahr 2003, nicht das Ausmaß früherer Extremereignisse, wie beispielweise 1921, 1947 oder gar 1540. Klimafolgenmodellierungen ergaben aber übereinstimmend generelle Abnahmen der Sommerabflüsse. Hieraus wird im Allgemeinen auf ein erhöhtes Risiko für Sommerniedrigwasser geschlossen. Allerdings waren Bestrebungen hinsichtlich einer gezielten Analyse projizierter Niedrigwasserextreme bislang sehr begrenzt, auch angesichts wesentlicher, hier speziell zu beachtender Unsicherheiten. Diese betreffen vor allem Defizite derzeitiger Klimamodelle in der Abbildung trockener Extreme, einen starken Einfluss des gewählten Downscaling-Verfahrens auf die zeitliche Sequenzierung sowie Schwächen üblicher hydrologischer Modelle und Kalibrierstrategien in der Abbildung des Abflussverhaltens unter extremen Niedrigwasserbedingungen. Zu diesen Unsicherheitsquellen speziell für die Abschätzung zukünftiger Niedrigwasser sind umfassendere Studien erforderlich.

Der jahreszeiten-übergreifende Einfluss der Schneedecke und der Dynamik ihres Abschmelzens ist ein wichtiger und zunehmend untersuchter, jedoch auch schwieriger, Aspekt bei der Erörterung und Attribution von Veränderungen sommerlicher Niedrigwasserabflüsse. Aufgrund des feuchten Sommerklimas ist der Effekt des Schnees des vorangegangenen Winters auf später im Jahr auftretende Niedrigwasser in der Schweiz bislang kaum zu isolieren. Hier ist auch ein besseres Prozessverständnis, wie sich veränderte Schmelzbedingungen auf Grundwasserneubildung und Basisabfluss auswirken, erforderlich. Zur Bewertung der Sensitivität verschiedener Gebiete wären detaillierte hydrogeologische Informationen, ein abgestimmtes Monitoring aller relevanten Wasserbilanzkomponenten sowie Informationen zu wasserwirtschaftlichen Eingriffen, die in Niedrigwasserzeiten besonders ins Gewicht fallen, wichtige Datengrundlagen. Diese sollten auch im Niedrigwasser hohe Qualitätsansprüche haben. Komplementär zur hinsichtlich Niedrigwasserextreme schwierigen und unsicheren Klimafolgenmodellierung sollten zukünftig zunehmend auch alternative Ansätze, wie Vulnerabilitätsstudien oder sogenannte Stresstestmodellierungen, verfolgt werden.

Resumé

Les basses eaux sont un phénomène normal du climat suisse, auquel les écosystèmes et l'utilisation de l'eau sont largement adaptés. Cependant, les situations de basses eaux de longue durée peuvent être associées à de nombreux défis en matière de gestion de l'eau, comme l'a montré l'été chaud et sec de 2003 et, plus récemment, en 2018. Ce rapport résume l'état de la recherche et les lacunes dans les connaissances sur l'impact du changement climatique sur les phénomènes de basses eaux.

Déterminés par le régime hydrologique, il existe en Suisse des schémas régionaux clairs en ce qui concerne le caractère saisonnier des basses eaux, qui se produisent généralement en été ou en hiver. L'analyse des tendances et la modélisation de l'impact sur le climat laissent présager une augmentation des écoulements en hiver en raison de l'augmentation des températures et des précipitations en hiver, entraînant une couverture neigeuse moins prononcée et, partant, une diminution généraledes basses eaux en hiver.

La gestion des réservoirs contribue également à la tendance à l'augmentation du ruissellement hivernal, mais dans une mesure difficilement quantifiable. L'émergence d'événements estivaux extrêmes est compliquée en raison d'une variété de processus et de facteurs pouvant exacerber ou atténuer les conditions de basses eaux. Des études récentes sur les changements induits par le climat dans les débits de basses eaux en été ont mis en évidence une tendance à la baisse dans certaines zones de basse altitude, mais ne donnent pas une image globale claire. Des analyses de tendance ciblées pour les basses eaux basées sur des séries chronologiques avec des données actuelles sont difficilement disponibles. La plupart des études sont basées sur des séries de données se terminant avant 2010 et ont tendance à examiner et à discuter des débits saisonniers et des changements de régime.

Sur le long terme, les événements estivaux récents tels que ceux de 2003 n'ont pas atteint le niveau des événements extrêmes précédents tels que 1921, 1947 ou même 1540. Cependant, la modélisation de l'impact sur le climat a montré une diminution générale constante des écoulements estivaux. Il est généralement conclu qu'il existe un risque accru de basses eaux en été. Toutefois, les tentatives d'analyse des conditions extrêmes de basses eaux ont jusqu'à présent été très limitées, même en présence d'incertitudes importantes appelant une attention particulière. Celles-ci concernent principalement les déficits des modèles climatiques actuels dans la reproduction de conditions extrêmes sèches, une forte influence de la méthode de réduction d'échelle choisie sur le séquençage temporel ainsi que les faiblesses des modèles hydrologiques courants et des stratégies d'étalonnage communes dans la reproduction du comportement des écoulements dans des conditions de basses eaux extrêmes. Ces sources d'incertitude, en particulier pour l'estimation des basses eaux futures, nécessitent des études plus approfondies.

L'impact de la couverture neigeuse pendant les saisons et la dynamique de sa fonte constituent un aspect important et de plus en plus exploré, mais également plus difficile, dans la discussion et l'attribution de changements dans les faibles débits estivaux. En raison du climat d'été humide, l'effet de la neige de l'hiver précédent sur les basses eaux survenant plus tard dans l'année a jusqu'à présent été difficile à isoler en Suisse. Cela nécessite également une meilleure compréhension de la manière dont les conditions de fonte changeantes affectent la recharge des eaux souterraines et le ruissellement de base. Pour évaluer la sensibilité des différentes zones, des informations hydrogéologiques détaillées, une surveillance coordonnée de toutes les composantes pertinentes du bilan hydrique et des informations sur les interventions de gestion de l'eau, qui revêtent une importance particulière en période de basses eaux, constitueraient des sources de données importantes. Ceux-ci devraient avoir des normes de qualité élevées, même en

basses eaux. En complément de la modélisation difficile et incertaine de l'impact climatique concernant les conditions extrêmes de basses eaux, des approches alternatives, telles que les études de vulnérabilité ou la modélisation dite de test de résistance, devraient de plus en plus être poursuivies à l'avenir.

1 Introduction

This report on low flow events is one of several contributions to a synthesis report "Climate Change and its consequences on Hydrology in Switzerland: Hydro-CH2018" in the framework of the National Centre for Climate Services under the auspices of the Hydrology Division of the FOEN (Swiss Federal Office for the Environment). Hydro-CH2018 aims to provide the hydrological basis for climate change adaptation measures and to establish a platform for knowledge sharing between researchers and users/stakeholders in the area of hydrology and climate change. Low flows are generally a normal phenomenon in a seasonal climate. Intact aquatic ecosystems are adapted to them and water management considers their occurrence similarly to design floods. Nevertheless, the extreme end of the spectrum of streamflow values is expected to be particularly sensitive to climatic changes. An exacerbation of low flows may present a number of challenges to water management as Switzerland experienced for example during the low flow event in the drought and heat summer of 2003 (BUWAL et al., 2004, see Section 2).

Definitions and terminology vary somewhat in the literature because low streamflows (low flows) can be considered in different ways and are described by a range of **different indices**. These indices, which are used in ecological flow assessments and the planning of infrastructure, are commonly derived from observed streamflow records or from modelled streamflow time series (Figure 1-1):

1) The average seasonal low flow magnitude and its timing: the annual minimum of the long-term hydrological regime based on monthly mean flow. Changes to these are also dealt with in the Hydro-CH2018 Chapter 'Runoff regimes'. Changes to the general low flow season have been assessed most so far, but don't necessarily allow conclusions on the full extent of changes in actual low flow events.

2) Statistical low flow values and indices: the streamflow corresponding to a quantile of the flow duration curve or a minimum streamflow value of the year or relatively in a particular season, derived from streamflow averages at various averaging time scales (daily, 7-days, 21-days). These metrics are used in practice for the frequency analysis of design-flows, as thresholds to restrict abstractions, or to trigger low flow warnings. For Switzerland, the value of Q_{347} is such a low flow value that is used to legally regulate minimum flow requirements for environmental flow determination.

3) Characteristics of extreme low flow and rare hydrological drought events: often described by duration and deficit volume under a certain flow threshold derived from 2), e.g. Q_{347} or mean annual minimum flow.

For definitions and symbols for low flow indices referred to in this report, see list at the end of the document. The FOEN provides low flow statistics for its gauging stations based mainly on the AM_7 low flow index (see https://opendata.swiss/de/dataset/niedrigwasserstatistik-nqstat). It should be noted that low streamflows are particular susceptible to **measurement inaccuracies**, depending also on the site and design of the gauging station, the reliability of the stage–discharge relationship at its lower spectrum, and the presence or absence of routine data plausibility and quality check procedures. Due to the issue of flow measurement uncertainty it is often recommended to use low flow indices based on averages over several days, e.g. AM_7, instead of the minimum recorded at a single day over a certain period, which can be strongly affected by outliers due to measurement issues.

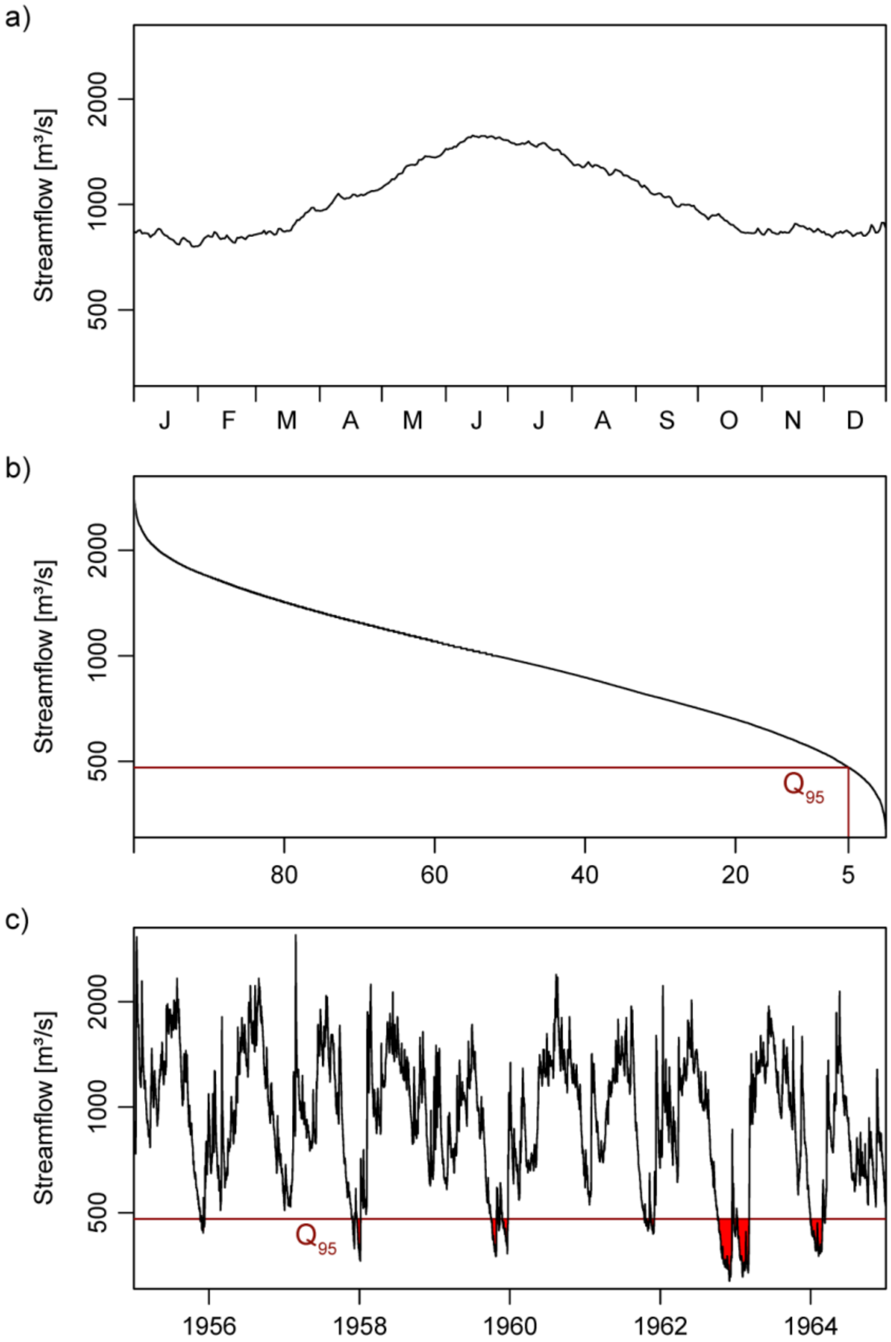


Figure 1-1: Exemplary streamflow data of the river Rhine at the gauge Basel: a) regime (mean daily flow 1911–2011) with within-year minima in autumn and winter, b) flow duration curve (1911–2011) with Q_{95} (in Switzerland also termed Q_{347}) flow value, and c) observed daily mean streamflow 1954–1965 with periods of flow below Q_{95} (1911–2011) highlighted. Note logarithmic scaling of y-axis.

In general, the choice of index should depend on the specific question being addressed. However, regarding low flow, climate change impact assessment studies should consider both:

i) The response of mean low flow to changes in the mean temperature and precipitation. This may allow assessments of the general water availability situation and is relevant for the future definition of environmental flows or any other statistical threshold. Changes to mean low flow are also addressed by those Hydro-CH2018 chapters and projects dealing with changes of hydrological regimes.

ii) The response of frequency and characteristics of extreme low flow events and associated drought risk to potential climate change, i.e. the response beyond the historical range, which is relevant for assessments of the impacts of future extreme events.

McPhillips et al. (2018) point out general cross-disciplinary differences in the definition of and communication on extreme events and particularly the lack of explicit definitions in academic literature. According to a workshop on extremes at the Hydro-CH2018 Kickoff meeting the analysis of climate projections from an '*event perspective'* remains one of the research gaps, in particular as many stakeholders request information on extremes. All indices that use a statistically derived flow threshold are based on the concept of stationarity. These indices require a baseline or reference period from which the low flow statistics are calculated, i.e. the normal low flow value. In a changing climate their derivation thus faces the issue of shifting reference values and there is an ongoing debate whether to keep the reference period values or whether to adapt these references over time (e.g. van Huijgevoort et al., 2014; Poff, 2018).

This report first revisits the drivers and processes underlying low flows (Section 2). It then reviews studies on past changes in low flow values and streamflow drought characteristics (Section 3) and on projected future changes from climate impact modelling (Section 4). Sections 5 and 6 discuss the changes found and identified research gaps from the perspective of specific conditions found in Swiss river basins.

2 Processes and drivers of low flow hydrology and past events in Switzerland

Keywords: deficiency, drought propagation, extreme event, heat wave, regimes, seasonality, storages

As an introduction, this section provides a brief overview of processes, drivers, and factors for the propagation of an atmospheric drought to a low streamflow event. Past work on low flow seasonality and experiences from some major past low flow events are summarised to identify key factors and major aspects for the assessment of low flow events in Switzerland.

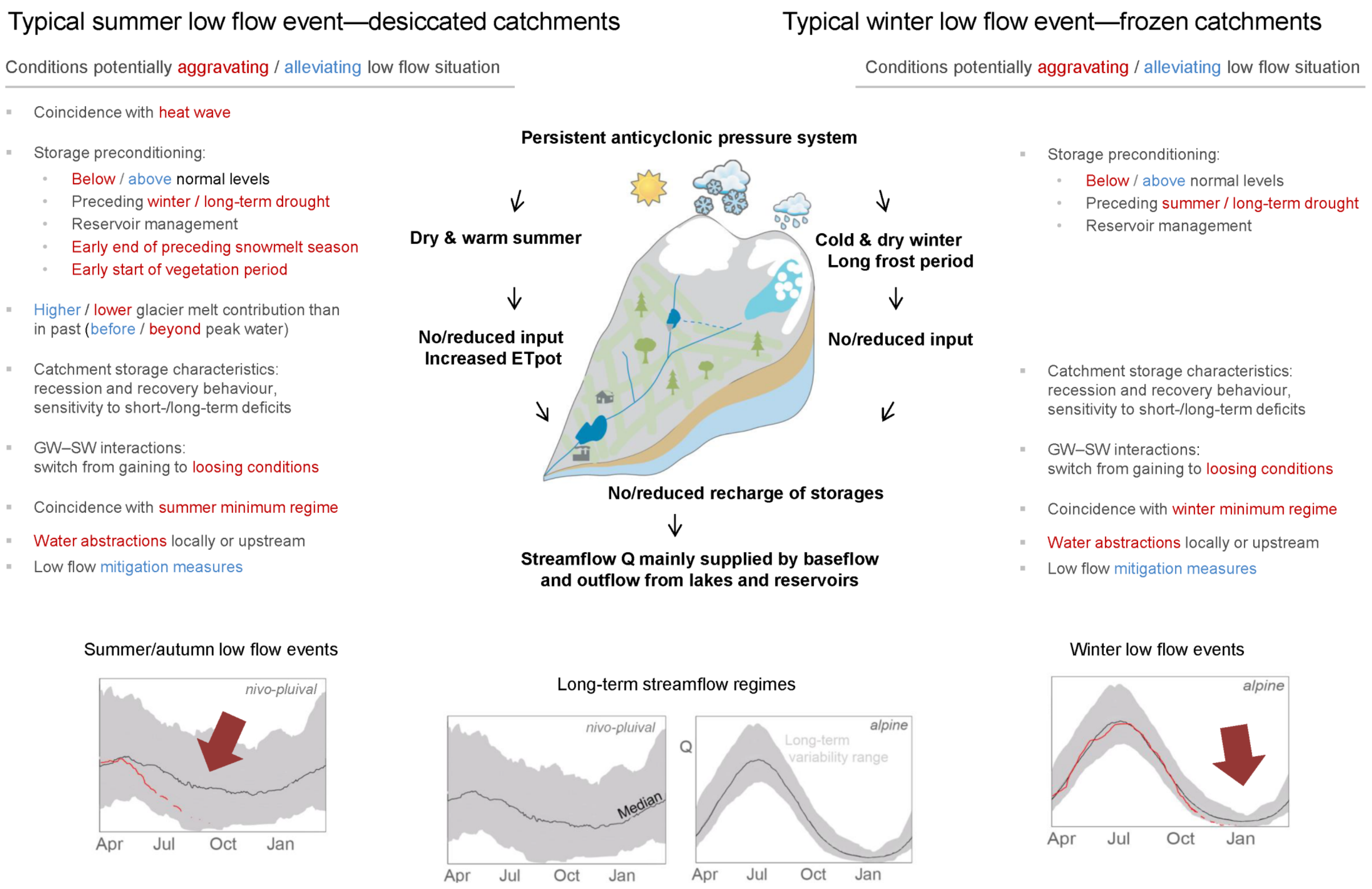
Comprehensive overviews on the **basics of low flow hydrology** have been given among others by Smakhtin (2001), Stahl (2001), Tallaksen and van Lanen (2004), Gustard and Demuth (2008), and Van Loon (2015). The occurrence of low flows results from a complex interaction between climate drivers and catchment storage processes after and during times of reduced catchment input, i.e. periods of low rainfall or periods of low temperatures, in which precipitation is stored in the snowpack (see Figure 2-1). Consequently, extreme low flows, also termed hydrological drought or streamflow drought, can be caused by extended dry periods as well as by extended freezing periods. In mid-latitude climates such extreme weather situations (cold spells, dry spells) are usually caused by persistent anticyclonic pressure systems, frequently associated with atmospheric blocking patterns. While climate controls input and atmospheric evaporative demand, catchment processes determine how resulting surpluses and deficits propagate through the vegetation, soil, and groundwater system to streamflow. Hence, the ‘dry weather streamflow’ response of a catchment is mainly controlled by preconditioning, memory, and recession characteristics of its storages (see also Section 6). A good understanding of these processes and catchments' characteristic responses is crucial for interpreting how changed environmental conditions may affect the frequency, duration, and intensity of low flow events.

Both types of low flow generating mechanisms, extended dry periods and extended periods with below freezing temperature, have played a role for low flow events in Switzerland in the past, as further explained in this section. In contrast, the large majority of literature relates low flows mainly to the occurrence of dry weather anomalies, commonly termed atmospheric **drought** or meteorological drought, defined as critical deficits in precipitation relative to a climatological norm at various time scales without differentiating between precipitation fallen as snow and rainfall. Starting from this atmospheric drought, conceptual classifications into soil moisture drought, agricultural drought, hydrological drought (streamflow and/or groundwater drought), socio-economic drought, and so on have been established and are commonly used terms in scientific literature. However, one should note that drought is a strongly context dependent phenomenon. Thus, the variety of suggestions and adaptions of drought concepts and drought indicators and the lack, or even impracticability, of a common objective quantitative definition of droughts (see Yevjevich, 1967; Wilhite and Glantz, 1985; Stahl, 2001; Smakhtin and Schipper, 2008; Sheffield and Wood, 2011; Seneviratne et al., 2012; Lloyd-Hughes, 2014) remain to be a considerable source of confusion. When focusing on streamflow, one should be aware that a differentiation between **streamflow droughts** (corresponding to low flow extremes) that are assessed through the conventional constant threshold level approach (Figure 1-1) **and streamflow deficiencies** that are assessed through a variable threshold level approach, and thus describe anomalies with respect to the season even during high flows, exists (Stahl, 2001; Hisdal et al., 2004). Many studies do not make this distinction when using the term streamflow drought.

In **hydrological research in Switzerland**, for a long time droughts and low flows have not been high on the agenda (Aschwanden and Kan, 1999a; OcCC, 2000; Meyer, 2012). In the 1990s investigations by Aschwanden (1992) and Aschwanden and Kan (1999a, b) targeted mainly a systematic quantification and regionalisation of **the low flow rate Q_{347}** (Q_{95}), which has been the base for the legal definition of minimum flow requirements (residual flow below water diversions and dams) since the adoption of the Federal Act on the Protection of Waters in 1991. These investigations and later studies by Pfaundler and Wüthrich (2006), Helbling et al. (2007), and Margreth et al. (2013) showed that the occurrence of low flows in alpine catchments is limited to the winter period between October and March. According to Aschwanden and Kan (1999a, b) the estimation of low flow indices, such as Q_{347} (Q_{95}) is easier for alpine streams with their (glacio-)nival controlled, simple, single-peak streamflow regime pattern. This regime is marked by annually recurring winter low flow periods, and relatively low interannual variability of low flows compared to streams in the other regions of Switzerland, i.e. the Jura Mountains and lower areas in the Swiss Plateau region and south of the Alps. In contrast to the clear dominance of winter as a **low flow season** in the Alps, Pfaundler and Wüthrich (2006) and Helbling et al. (2007) found a less pronounced seasonality for streams in the Jura, with low flows typically in autumn, and an only weak seasonal tendency of predominantly autumn/summer low flow occurrence in the Swiss Plateau region. Principially, in the non-alpine catchments low flow events can occurr in any season. Therefore, the role of catchment storages and processes becomes more prominent in these regions characterised by a higher interannual variability of low flows as well as more heterogenous/complex spatial patterns of low flow seasonality and magnitude of low flow and baseflow indices compared to the Alps (Aschwanden and Kan, 1999a, b; Pfaundler and Wüthrich, 2006; Meyer et al., 2011a).

Systematic research on low flows in Switzerland has dealt mainly with low flow statistics in terms of seasonality (Pfaundler and Wüthrich, 2006) or quantification of low flow indices as Q_{95} (Aschwanden, 1992; Aschwanden and Kan, 1999a, b; Margreth et al., 2013; Naef et al., 2015; 2015; Naef and Margreth, 2017) or AM_7 (Helbling et al., 2007). Low flow statistics are closely related to streamflow regime characteristics, and thus the analysis of changes of low flow indices is linked to the analysis of changes of regimes (see Hydro-CH2018 contribution on streamflow regimes). Systematic changes of low flow indices are relevant for the definition of thresholds and environmental flows and adaption of water management. However, the analysis of processes and situations that lead to the occurrence of **extreme low flows from an event perspective** may be of even higher interest. As described above, such extreme low flow events can be caused either by abnormally long periods with below freezing temperature or by abnormally dry periods. In addition, especially during the warm season, increases in potential evapotranspiration can initially lead to increased losses and the development of a soil moisture drought with then limited actual evapotranspiration, which may contribute to the development or persistence of heat waves. However, it should not been overlooked that the role of evapotranspiration and temperature in the context of droughts is a complex topic itself, which cannot be simplified (Seneviratne, 2012) and is also treated in more detail in the Hydro-CH2018 contribution on soil moisture and evapotranspiration.

Based on the major mechanisms potentially leading to low flow situations, one can in a simplified manner distinguish between **typical winter low flow events**, mostly relevant for catchments with winter regime minimum, and **typical summer low flow events**, mostly relevant for catchments with regime minimum during or after the growing season (Figure 2-1).



Typical summer low flow event—desiccated catchments

Conditions potentially aggravating / alleviating low flow situation

- Coincidence with heat wave
- Storage preconditioning:
  - Below / above normal levels
  - Preceding winter / long-term drought
  - Reservoir management
  - Early end of preceding snowmelt season
  - Early start of vegetation period
- Higher / lower glacier melt contribution than in past (before / beyond peak water)
- Catchment storage characteristics: recession and recovery behaviour, sensitivity to short-/long-term deficits
- GW–SW interactions: switch from gaining to loosing conditions
- Coincidence with summer minimum regime
- Water abstractions locally or upstream
- Low flow mitigation measures

Persistent anticyclonic pressure system

Dry & warm summer

No/reduced input
Increased ETpot

Cold & dry winter
Long frost period

No/reduced input

No/reduced recharge of storages

Streamflow Q mainly supplied by baseflow and outflow from lakes and reservoirs

Typical winter low flow event—frozen catchments

Conditions potentially aggravating / alleviating low flow situation

- Storage preconditioning:
  - Below / above normal levels
  - Preceding summer / long-term drought
  - Reservoir management
- Catchment storage characteristics: recession and recovery behaviour, sensitivity to short-/long-term deficits
- GW–SW interactions: switch from gaining to loosing conditions
- Coincidence with winter minimum regime
- Water abstractions locally or upstream
- Low flow mitigation measures

Summer/autumn low flow events

Long-term streamflow regimes

Winter low flow events

Figure 2-1: Scheme of catchment storages, processes, and factors for typical winter and summer low flow events.

Of course, in reality the generation of extreme low flows rarely follows exactly such 'textbook schemes' but may be caused by a combination of both types, e.g., a summer drought followed by an early onset of the winter season (frost conditions) or be the result of deficits accumulated over longer time scales (multi-year groundwater droughts). Some of the various factors that may partly compensate for deficits or amplify low flow severity are listed in Figure 2-1.

Information on extreme low flow events in Switzerland and their impacts can mainly be found in analyses and synthesis reports of **major past events** (e.g. Schorer; 1992; Marti and Kan, 2003; BUWAL et al., 2004; FOEN, 2016; Zappa and Kan, 2007; Weingartner and Pfister, 2007). These major events of the last 100 years include the summer drought and low flow events in the years 1947 and 2003 and the winter low flow events in 1962/63 and 2005/06. For these selected events the smoothed hydrographs of three exemplary gauges with differing flow regimes are shown in Figure 2-2. The clear dominance of winter low flows in alpine catchments is evident. In contrast, conditions are more variable in non-alpine catchments and in larger river basins with complex flow regimes. In addition, Figure 2-2 illustrates that the evolution of real low flow events is usually not as straightforward as sketched in Figure 2-1 but often a combination of deficiencies and low flows in several seasons interrupted by periods of partial recovery.

According to a study on **past winter low flow events** for the long flow record of the river Rhine at Basel, the events in 1963 and 2006 were the only two extremes that occurred after 1910 compared to eleven winter low flow events in the period 1808–1909 (Pfister et al., 2006). As the data in Figure 2-2 show, marked streamflow deficiencies already in autumn 1962, or earlier, preceded the winter low flow event in 1963. Based on the analysis method for meteorological droughts in the greater alpine region by Haslinger and Blöschl (2017), the summer of 1962 was even the most intense summer drought of the period 1801–2010, drier than, for instance, the drought of 2003, although temperature anomalies were slightly below average. This summer drought was followed by an extremely cold and dry winter. Between 1962 and 1964 Central Europe was affected by three dry spells and very unusual meteorological winter conditions (Stahl, 2001). An assessment of the more recent winter event 2005/06 in a long-term context was presented by Weingartner and Pfister (2007). In February 2006 water levels of Lake Constance sunk to levels only slightly above the lowest on record (from Feb 1858) with remarkable impacts on ferry operation (Pfister et al., 2006; Weingartner and Pfister, 2007). However, regarding the Rhine's discharge at Basel the winter event in 2005/06 was less severe than that of 1962/63 (Figure 2-2) and only 12th in the ranking of the lowest AM_7 flow values since 1808 (Pfister et al., 2006). It should be noted that an observed increase in the Rhine's winter low flows, in particularly from 1945 onwards, can partially be attributed to the effects of hydropower (Pfister et al., 2006; Belz et al., 2007). Pfister et al. (2006) concluded that the winter 2005/06 compares well to the other thirty extreme low flow events that could be reconstructed for a period back to the 16th century; comparisons with reconstructed data on sea-level pressure fields, temperature, and precipitation for Europe showed that in most cases, also in the winter 2005/06, these extreme events were associated with blocking anticyclones persisting over several months.

Authors agree that meteorological conditions have changed over the 20th century towards warmer and wetter winters with less frequent cold winter droughts than in earlier centuries (Pfister et al., 2006; Haslinger and Blöschl, 2017); a trend not expected to be reversed under climate change. Neither much information on winter low flow events at other (smaller) rivers in Switzerland, nor much information about the impacts of winter low flows, besides impacts

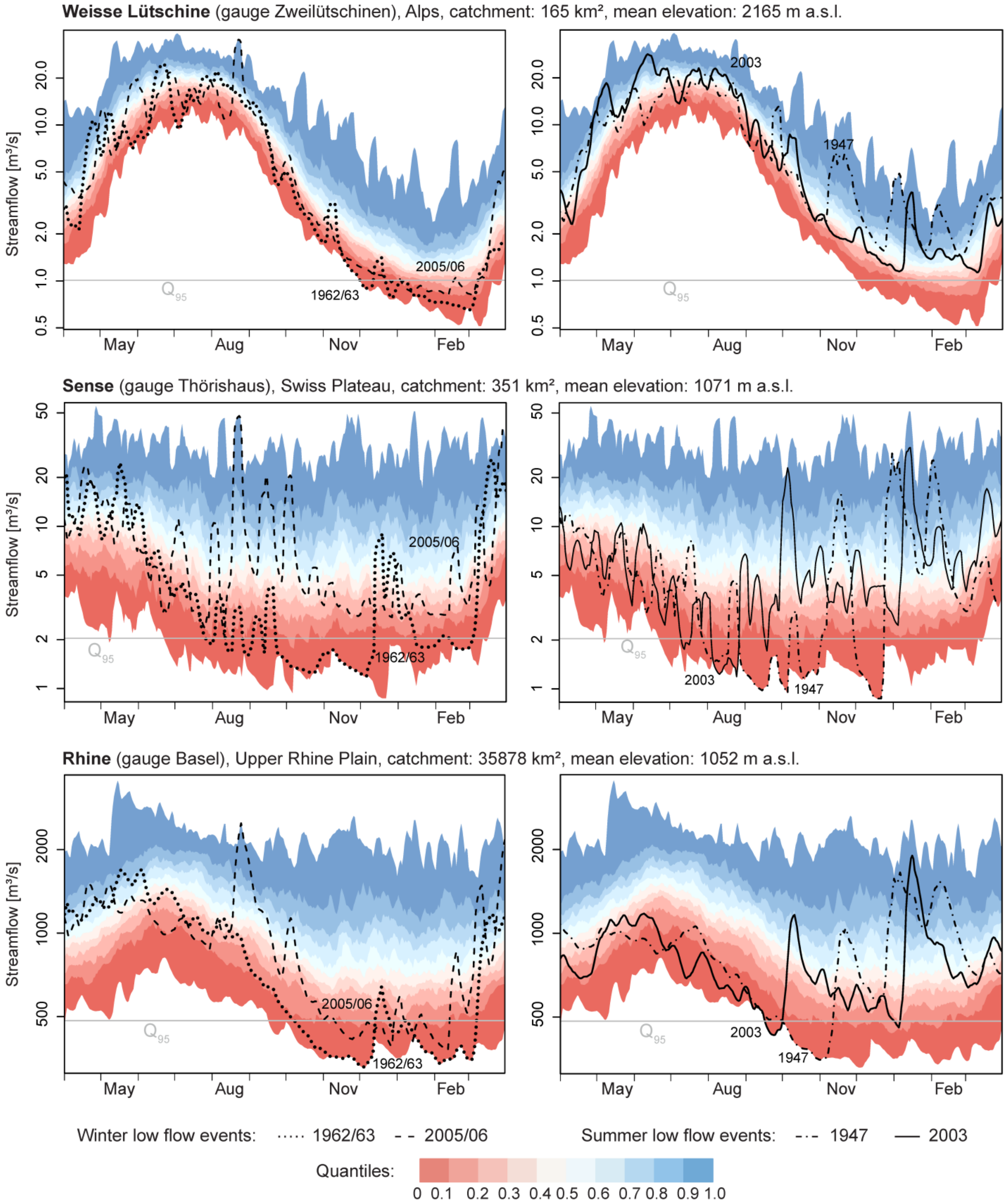


Figure 2-2: Weekly mean streamflow for past low flow events in Switzerland, winter 1962/63, winter 2005/06, summer 1947, and summer 2003, against weekly mean flow quantiles and Q_{95} (Q_{347}) derived from the flow duration curve (daily mean) based on the streamflow records 1933–2012 for exemplary streams with alpine, glacio-nival (Weisse Lütschine), nivo-pluvial, préalpine (Sense), and complex (Rhine) flow regimes. Note logarithmic y-axis scaling! Original time series data: daily mean flow, provided by FOEN.

on inland navigation, are available. Pfister et al. (2006) suggest that in earlier, preindustrial times the impacts of winter low flow events may have been of higher relevance, e.g. due to the important societal role of small-scale run-of-the-river power plants. The latest winter low flow event in Switzerland occurred in December 2016 / January 2017 when low flows across Switzerland were predominantly in the range of return periods between 2 and 10 years with more extreme low flows (up to 300 year return period) at individual stations and even new low water level records at some of the large lakes (FOEN, 2017). This event was a result of a combination of precipitation deficits in autumn/winter and winterly freezing conditions.

The **summer droughts and low flow events of 1947 and 2003** shown in Figure 2-2 are among the most eminent in the recent past, relatively well documented in literature, and in many studies regarded as benchmark events. In the so-called Central-European climatic optimum period, in addition to the 1947 event, Switzerland was affected by droughts in the years 1949 and 1953 (Schorer, 1992). Exacerbated by the post-war situation and following the 'Hungerwinter of 1946/47' (see also Bundesrat, 1947), the drought in 1947 developed mainly as a result of long, persistent dry and warm spells over the growing season, rather than of record-setting extremes (Schorer, 1992). According to the assessment and drought indicators by Pfister and Rutishauser (2000) it represents the most intense meteorological summer drought in the Swiss Plateau region during the period 1864–1995. However, regional differences were important for the understanding of low flows. Precipitation deficits affected the alpine areas slightly less than regions further to the north. Positive temperature anomalies, prevailing from April to October 1947 all over Switzerland were particularly large in the alpine region. This led to intensified snow and glacier melt, and thus augmented streamflow with a larger effect on the mitigation of low flows than the regional contrasts in precipitation deficits (Schorer, 1992). Schorer (1992) detected that the ice melt season in 1947 was prolonged by up to two months compared to the long-term mean duration (1901–60). Accordingly, the year of 1947 was characterised by extremely negative glacier mass balances in the European Alps (Huss, 2012; Stahl et al., 2017b). Up to the present, 1947 has been the year with the earliest snow disappearance date recorded at the alpine snow monitoring station at the Weissfluhjoch (Marty and Meister, 2012). The early end of the snowmelt season in 1947 and the long duration of the meteorological drought led to extremely low flow levels in late autumn, as can also be seen in the data of the streamflow gauges of the Sense and the Rhine (Figure 2-2). In contrast, streamflow of glacierised catchments, such as the Weisse Lütschine (Figure 2-2), was at normal, and frequently above normal levels due to increased ice melt contributions (Schorer, 1992; Stahl et al., 2017b).

The evolution, progression, and impacts of the combined drought and heat in Central Europe in the summer of 2003 have been subject of a large body of reports and academic work, e.g. by BUWAL, BWG and Meteo-Schweiz (2004). In Switzerland the streamflow drought peaked in August 2003 but with less extreme low flows than those of autumn 1947 (see also Figure 2-2). Similar to the low flow situation in 1947 the Swiss Plateau was most severely affected, whereas in alpine streams abnormally high flows were recorded due to increased glacier melt (BUWAL et al., 2004; Zappa and Kan, 2007; Stahl et al., 2017a, b). Although precipitation anomalies, streamflow deficiencies, and low flow return periods in 2003 did not nearly match the extent of 1947 (Marti and Kan 2003; Helbling et al., 2007; Calanca, 2007), impacts due to low water levels and high water temperatures among others on agriculture, navigation, stream ecology, water supply, and energy production as well as various water use conflicts (BUWAL et al., 2004) revealed the vulnerability of Swiss water resources managements systems to such combined drought, low flow, and heat wave events. In consequence of 2003 as an alarming event, drought and low flows have gained more attention as research topic and challenging action field in Switzerland, and in this context several projects and initiatives have followed (FOEN, 2012b; Meyer et al., 2011b; Seneviratne et al., 2013; Dübendorfer et al., 2016; Chaix et al., 2016; Wehse et al., 2017; Staudinger et al., 2018).

Other summer low flow events in the recent past occurred in the years of 1976 (Schorer, 1992) and 2015 (FOEN, 2016), which in terms of their impacts are described as less severe than the events of 1947 and 2003. Compared with the development of the drought in 2003, relatively wet conditions prevailed in spring 2015, while the low flow event extended longer into autumn and even beyond. According to the report by FOEN (2016) catchments with pluvial regimes reached levels below the Q_{347} flow rate already in July, whereas low flow conditions in catchments influenced by melt water, large lakes, or large aquifers were reached later, at the end of the summer or in November. As in the events of 1947 and 2003, alpine streams benefited from increased glacier melt contributions and their flows were mostly not abnormally low. Interestingly, some aquifers and springs towards the end of 2015 were affected more than in 2003. The low flow event in 1976 stands out among the summer events described here due to a different character of drought development and also an example case for a drought and low flow year that was not associated with substantial summer heat surpluses and significantly increased runoff contributions from glacier melt (Schorer, 1992; Stahl et al., 2017b). The event evolved as a long-term drought with fluctuating weather conditions leading to a cumulative streamflow deficit that was overall larger than in the years 1947 and 2003, but streamflow levels rarely dropped to extremely low levels.

Within the context of extremes and climate variability an important question is how the **severities of past events** rank in a long-term perspective. In contrast to floods when mostly the peak water level is of interest, different indices are needed to characterise droughts and low flow events. These indices need to reflect characteristics besides minimum flow, such as indices of deficit volume under a low flow threshold and duration. Different indices can be used to assess the severity of a low flow event, depending on the potential impacts of interest. In addition, it should be noted that available observed flow records are usually insufficient for reliable frequency quantification of extreme low flows events and, therefore, theoretical distribution functions are needed to extrapolate beyond the limits of 'observed' probabilities (Smakhtin, 2001; Tallaksen and van Lanen, 2004). Marti and Kan (2003) compared the low flow events of 1947 and 2003 based on an assessment of return periods of the AM_{30} low flow rate. According to their results AM_{30} of all analysed non-alpine streamflow gauges for the year 1947 correspond to return periods ≥10 years, among which five had return periods of even ≥100 years; calculated return periods for the 2003 event at all analysed stations were lower than those for 1947, at only six stations ≥10 years, and not ≥50 years for any station. Calculated return periods for AM_7, AM_{14}, and AM_{30} for both events by Helbling et al. (2007) yield a similar pattern. For some larger rivers and lakes in Switzerland the occurrence of extreme low flow events could be reconstructed for the pre-instrumental time horizon (Pfister et al. 2006; Stucki and Luterbacher, 2010; Wetter, 2017). Overall, the existing studies on past low flow events indicate that the events experienced during the instrumental period, in particular those in the years 1947 or 2003, represent events of only moderate severity in a long-term context. This review of past events underlines the need to study the impact of climate change on low flows from an event perspective and beyond the general streamflow seasonality. It also suggests that while the event of 2003 provides important reference for characteristics and impacts, it may not be a sufficient worst-case scenario.

Take-home messages

- Switzerland has been characterised by clear regional patterns with a general seasonality of summer or winter low flows related to the respective hydrological regimes. Long-term glacier storage change, seasonal storage as snow, and soil and groundwater storage release water at varying time scales. This release may sustain streamflow during in the absence of rainfall–runoff generation processes in the catchment.

- The generation of summer low flows is more complex than that of winter low flows. The development of extreme low flow events is a result of several processes and factors that may compensate or amplify low flow severity. This complexity of changes in drought and low flow conditions does not allow simplifications and conclusions on future low flow risk based on only individual drivers (e.g. only warming but not precipitation changes).
- In terms of overall impact, summer events have been more memorable than winter events in the past. Winter events were less frequent in the 20th century than earlier—a tendency expected to continue with warming.
- Recent extreme events, particularly the one of 2003, had a wide range of impacts and have revealed vulnerability. However, in terms of return period these events did not match the extreme magnitude of historical events in a long-term context and may therefore not be adequate worst-case scenarios for the future.

3 Past changes in low flows derived from streamflow time series analyses

Keywords: attribution, flow indices, near-natural flow, time series, trend analysis, trend test, detection

This section reviews the time series analyses of past streamflow records. Table 3-1 summarises the study designs and major results. Overall, few studies focused on trends in low flow values in particular but most studied trends in a range of different flow indices. Several studies analysed data from Switzerland's headwater catchments with only little influence of regulation (Birsan et al. 2005; Pellicciotti et al., 2010; Stahl et al., 2017b; Hänggi and Weingartner, 2012; Weingartner, 2017); others studied records from gauges along the River Rhine and some of its major tributaries (Pfister et al., 2006; Belz et al., 2007; Hänggi and Weingartner, 2011; ICPR, 2018). Another set of studies considered data from regions with similar geographical settings, which are included here to identify any evidence of consistently observed changes with respect to low flow. The latter cover the pan-European scale (Stahl et al., 2010; Hannaford et al., 2013) the wider alpine region (Bard et al. 2015), and neighbouring countries (Giuntoli et al., 2012; Renard et al., 2008; Blaschke et al., 2011; Blöschl et al., 2011; Laaha et al., 2016; Kormann et al. 2015a,b; Bocchiola, 2014; KLIWA 2017; LfU 2014).

The largest consensus among the reviewed studies is that in Switzerland annual **winter low flow** magnitudes predominantly have increased. The dominance of these increases is based mainly on the analysis of trends in annual winter flow quantiles and minima and it appears to be a direct reflection of a generally increased winter streamflow level in particular since the mid-1980s. In headwater catchments authors explained these increasing trends mainly by climatic trends, i.e. warmer winter temperatures (e.g. Birsan et al., 2005; Bard et al., 2015; Hänggi and Weingartner, 2012; Belz et al., 2007; Pfister et al., 2006; Blöschl et al., 2011). However, a formal statistical attribution of this reasoning based on the assumption of an increasingly larger share of rainfall runoff generation during winter has not been performed as there is no straight-forward method to do this. A comparison of co-variability with snowpack may provide some indications. Klein et al. (2016) found a decline in all snowpack parameters of alpine observation data over the period 1970–2015. With the increase of winter air temperatures in the 1980s, snow cover at mid and low elevations in Switzerland also changed (e.g. Laternser and Schneebeli, 2003; Scherrer and Appenzeller, 2004; Marty, 2008). This trend reversed again from 2000 to 2009 (Scherrer et al., 2013), stressing the high decadal variability superimposed on climate change signals. Exceptions to the consensus of increasing winter low flows are highly glacierised catchments at high elevations, for which results are less clear. Some analyses of time series ending in the first decade of the 21st century did not detect any significant changes of winter low flows (Pellicciotti et al., 2010; Hänggi and Weingartner, 2012), whereas Bard et al. (2015) detected field significant trends over the period 1961–2005 for their sample of glacier and snow-dominated regimes. Where applicable, reservoir management is assumed to have amplified the climate-driven trend by increased release of stored water for hydropower production in winter. Estimates of the mean increase in the Rhine's winter streamflow at Basel through water release from Alpine reservoirs amount to about 70 to 80 m³/s, which would correspond to a substantial contribution to the observed increases in AM_7 (Pfister et al., 2006). Apart from such rough estimates, however, the share of this additional flow contribution to observed trends in low flows has not been quantified yet, neither at the scale of headwaters nor along large rivers.

Table 3-1 Summary of reviewed streamflow time series analyses with respect to findings relevant for low flows; additionally analysed hydroclimatic variables or high flow indices not included here. All studies based on originally daily mean streamflow data, unless indicated differently. MK: Mann–Kendall; for methodological details (testing procedure etc.), see original references.

Reference	Streamflow time series sample	Trend analysis methods	Analysed flow indices	Period(s)	Findings
*Streamflow time series studies covering headwater catchments in **Switzerland** without substantial influences of abstraction and regulation*					
Hänggi and Weingartner (2012)	51 catchments across Switzerland covering all regime types (mean elevations: 370–3235 m a.s.l.)	Bootstrap approach to generate 2.5% and 97.5% confidence bounds for the reference period to test for difference (anomalies) of individual periods	Flow duration curve and Q_{95}, number of days with flow < Q_{95} (1995–2009)	1935–1949 1950–1964 1965–1979 1980–1994 ref.: 1995–2009 and moving 15 yr periods	For nearly all times series and the periods 1931–1945 to 1963–1977, significantly more days fell below the Q_{95} value of the later reference period. For many time series representing conditions **in the Swiss Alps significantly lower flows are visible in the periods prior to 1986–2000 compared to the later reference period** (1995–2009). Mostly no sig. changes were detected in analysed winter flow series of high alpine catchments (mean elevation ≥ 2400 m a.s.l.).
Birsan et al. (2005)	48 across Switzerland (mean elevations: 473–2718 m a.s.l)	MK trend test incl. prewhitening, at-site test ($\alpha = 0.1$) and field significance tests ($\alpha = 0.05$)	Quantiles incl. maximum and minimum at annual and seasonal scale	**1971–2000** subsets: 1931–2000 1961–2000	Overall increase in annual streamflow mostly due to increases in winter, winter increases are most dominant/distinct. Sig. **trends in summer moderate and low flow quantiles in both, up and downward, directions**, decreases slightly dominating, and increases concentrated on glacierised catchments. Although gauges without major water management interventions were chosen, excluding human influences altogether is not possible.
Pellicciotti et al. (2010)	Five alpine catchments including major glaciers in Switzerland (station elevations: 1317–2400 m a.s.l.)	MK trend test with and without prewhitening, results shown for the latter ($\alpha = 0.1$)	Mean and quantiles at annual and climatologically defined seasonal scale	**1974–2004** site-specific 30 yr periods between 1934 and 2004	Marked differences in the behaviour of 4 highly glacierised catchments and catchment with smaller glacier coverage (~10%, Landquart, Silvretta glacier). Sig. increases in spring and summer flow for most quantiles. Clear sig. increases in winter lower quantiles at Rhone glacier in contrast to absence of sig. trends in winter flows at all other sites.
Stahl et al. (2017b)	25 catchments in Switzerland (mean elevations: 590–2945 m a.s.l.)	Theil–Sen algorithm, MK trend test ($\alpha = 0.05$)	Average flow per calendar week	1900–1925 1925–1954 1955–1984 **1985–2012**	**Trend patterns differing for catchments and subperiods**. Results for all catchments summarised only for summer (weeks ~ 28–31) 1985–2012: differing in direction andmagnitude, for a few glacierised catchments distinct negative trends.
*Streamflow time series studies for gauges of the **River Rhine** and some of its major tributaries*					
Belz et al. (2007)	Gauges of the River Rhine and its larger tributaries	MK trend test ($\alpha = 0.05, 0.20$), Pettitt change point test ($\alpha = 0.20$) among others	Annual and monthly means,annual AM_7 and AM_{21}, timing of AM_7, low flow indices based on water balance year Apr–Mar	**1901–2000** **1951–2000** and subperiods dependent on obs. record	For gauges in the southern part of the Rhine basin with nival **regimes with winter flow minimum**: **predominantly increasing tendency of low flow indices**, often significant. Increases of winter low flows are **consistent with** observed changes in monthly means, i.e. **regime shift** towards more/less flow in winter/summer and a decreased within-year variability. These changes were related mainly to **warmer and wetter winters and hydropower operation**

Reference	Streamflow time series sample	Trend analysis methods	Analysed flow indices	Period(s)	Findings
*Streamflow time series studies for gauges of the **River Rhine** (continued)*					
Pfister et al. (2006); Weingartner and Pfister (2007)	Gauge Rhine@Basel	12 different trend test procedures	Annual AM_7 based on the hydrological year Oct–Nov	**1869–2007**	Sig. positive trends for 1869–2007 but with two distinct sub-periods and a breakpoint around 1909. For 1910–2006 only half of the applied tests detected a sig. trend. Sig. **positive trends for periods starting between 1945 and 1970 and ending in the 1980s**. Considering estimates of hydropower effect and use of a regression model suggests that increase **in (winter) low flows** can be **explained by warmer and wetter winters**, esp. in the 2nd half of the 20th century, **but** a considerable proportion may **also** be related to **hydropower**.
Hänggi and Weingartner (2011)	Gauge Rhine@Basel (monthly mean values)	Graphical analysis of moving 30 year annual and seasonal flow distributions, standardised based on 1961–1990 ref. period, bootstrap test method to detect differences to ref. period	Analysis of interannual variability based on annual and seasonal flow for moving 30 year windows distributions' L-moments: L-mean and L-scale after detrending of individual 30 year periods	**1808–2007** moving 30 year periods	Changes in the distributions found in **winter and spring,** when **streamflow, precipitation, and temperature have increased** considerably. L-moments representing summer/ autumn flow conditions did not vary significantly during the past 200 years. Regarding year to year variability: no sig. changes but most pronounced change with an increased variability in spring. Distributions of streamflow and precipitation only in winter and spring significantly related. Overall, **no 'rules' in the behaviour of the interannual variability** could be found.
*Streamflow time series studies covering **wider Alpine region** (including Swiss catchments)*					
Bard et al. (2011, 2015)	177 catchments across Alpine Space (AdaptAlp dataset) classified based on flow regime	Modified MK trend test at-site test (α = 0.1) and field significance tests for whole sample and for each regime	Annual quantiles, low flow indices: minimum, deficit volume, and low flow duration (threshold: 0.15 interannual quantile), regime-specific seasonal time windows	**1961–2005** subsets: 1925–2005 1925–1964 1965–2005	**Spatially consistent patterns for regime changes** suggest control of climate. Field sig. trends towards **less severe winter low flows** for regimes highly influenced by snowmelt and glaciers, less clear trends for regimes with lower dominance of snowmelt. For regimes with strongest pluvial influence: Tendency towards more severe summer low flows, but results not shown/detailed; increasing severity of winter low flows in the south-eastern part of the study region.
*Streamflow time series studies covering **pan-European scale** (including Swiss catchments)*					
Stahl et al. (2008, 2010)	441 small catchments with near-natural streamflow records from 15 countries across Europe (European Water Archive network)	Theil-Sen algorithm to calculate standardised trend magnitudes without testing for statistical significance	Annual and monthly mean flows, low flow indices for May–Nov summer season: AM_7, calendar day of AM_7, and AM_{30}	**1962–2004** subsets: 1932–2004 1942–2004 1952–2004	Overall coherent pattern of changes in annual flow with increases/decreases in northern/southern and eastern parts as well as in the trends of monthly flow, particularly **increasing winter flows**. **Changes in summer AM_7 are mixed but with widespread decreases** for catchments with summer-minimum regime across Europe, **timing of AM_7** shifted to an **earlier** date in the majority of the catchments.
Hannaford et al. (2013)	132 catchments from Stahl et al. (2010) with data from 1932–2004, mostly located in Scandi-	Calculation of MK Z statistic for standardised and smoothed time series without testing for statistical significance	Annual and monthly mean flows, AM_7 for May–Nov	≥ 20 yr periods for all possible start/end combinations within 1932–2004	Results of the **multi-temporal trend analysis** demonstrated considerable variability of trends in time in all regions. The recent past has had a strong influence on long-term trends. Studies based on post-1960 records/periods show trends that are not present in long periods, e.g. when incl. the dry 1940s. Consequently, recent short-term

	navia and Central Europe, clustered into five regions				trends should always be amended by analyses that place them in a long-term context.

Reference	Streamflow time series sample	Trend analysis methods	Analysed flow indices	Period(s)	Findings
*Streamflow time series studies covering **adjacent regions/countries** of Switzerland*					
Bocchiola (2014)	11 **alpine** catchments in **Northern Italy** (mean elevations: 942–2246 m a.s.l)	Linear regression, MK trend test (α = 0.05), iterative break point analysis	Annual and seasonal mean flow	**Various** between 1921 and 2011	**Predominantly decreases in annual and seasonal flow** (all seasons), partially (2 to 5 out of 11) significant. Out of initially 23 time series, 12 had been discarded from trend analysis due to non-negligible flow regulation effects.
Blöschl et al. (2011), Laaha et al. (2016)	463 gauges across **Austria**	MK trend test incl. prewhitening (α = 0.05, two-tailed)	Annual Q_{95} low flow index (0.05 quantile)	**1950–2007** **1976–2007**	**Predominantly non-sig. trends**. Some **tendency for sig. increasing trends of Q_{95}** for catchments **> 900 m a.s.l.** (34%/14% of gauges) **and sig. decreasing trends** of Q_{95} for catchments **< 900 m a.s.l.** (13%/11% of gauges) in both periods (1950–2007/1976–2007).
Kormann et al. (2015a, b)	32 **alpine** catchments in **Western Austria** mainly North Tyrol (mean elevations: 1467–3127)	MK trend test incl. prewhitening (α = 0.1; field significance α = 0.1)	Annual mean flow, annual series of phase and amplitude of a first order Fourier model fitted to data to explore timing changes	**1980–2010**	Annual average flows: Increases in higher-altitude catchments vs. decreases in lower-altitude ones. Although detecting and attributing changes in alpine streamflow found to be challenging, detailed analysis showed that altered dynamics are mostly driven by temperature
Renard et al. (2008)	64 gauges across **France** grouped in hydroclimatic region subsets	Newly introduced semiparametric regional likelihood ratio test (α = 0.1, 0.05, 0.01)	Annual low flow indices: AM_7 and its angular date, low flow duration and deficit volume (threshold: 0.15 quantile)	27 to 90 common years per subset	**Less severe low flows** (decrease in annual low flow duration or deficit volume) **detected for alpine gauges**. Increases in low flow duration and/or deficit volume found for gauges in Pyrenees and Basque regions.
Giuntoli et al. (2012)	220 gauges across **France** from national low flow reference network of catchments with near-natural flow records (of which 36/184 classified as snowmelt- influenced/ rainfall dominated)	Modified MK trend test, additionally Kendall's tau test for correlations between hydrological and climate indices (α = 0.1, 0.05, 0.01)	Annual indices: mean and minimum flow, deficit volume, low flow start, centre, and end (threshold: 0.15 quantile), regime-specific definition of hydrological year	**1968–2008** subset: 1948–1988 1968–2008 1948–2008	Sig. increase in low flow severity detected for many gauges in southern France over 1968–2008, yet trends are not stable over periods. **Sig. trends towards earlier start of low flows** detected for 30% of the gauges, mainly in eastern part over 1968–2008, while over 1948–2008 sig. earlier low flow start detected only for 3 snowmelt-dominated gauges. Based on correlation with climate indices: increasing low flow severity may partly result from large-scale climate variability.
KLIWA (2011, 2017)	30 gauges in **southern Germany**	Linear trend analysis, MK trend test	Annual low flow indices: minimum flow, AM_7, and low flow duration (threshold: MNQ)	1951–2010 1951–2000 1951–2015 1974–2015	Overall only **few gauges with sig. trends**. Conclusions on climate driven changes of low flows are not possible because influence of measurement uncertainty, water use, and even targeted low flow mitigation cannot be excluded.
LfU (2014)	70 gauges across **Bavaria**	MK trend test, seasonal MK trend test, t-Test among others	AM_7, timing of AM_7, and low flow duration (threshold: MNQ: interannual mean of annual minima), annual analysis based on Apr–Mar, summer/winter: Apr–Sep/Oct–Mar	Record start (≥1900) **–2006**	Predominantly no sig. trends in AM_7 detected. In northern / southern region some gauges with sig. increases / decreases. In contrast, **sig. trends in AM_7 timing detected for a majority of the gauges** with mainly later occurrence of summer low flows (northern part) and earlier occurrence of winter low flows (southern part). Detected trends could only to a minor part be related to changes in climatic variables. Human impact cannot be excluded, influence on changes likely.

Section 2 already noted that conditions have generally changed towards warmer and wetter winters with less frequent cold winter droughts and low flow events than in earlier centuries (Pfister et al., 2006; Haslinger and Blöschl, 2017). However, the recent winter low flow events of 2005/06 (Pfister et al., 2006) and 2016/17 (FOEN, 2017) are evidence that severe low flow situations in winter can still occur nowadays.

Changes in historical **summer low flows** from the reviewed studies are more variable. Trend signals of mean summer streamflow are more heterogeneous. The trends found are somewhat more consistent for a particular regime type. Based on the streamflow time series of a few highly glacierised catchments, Pellicciotti et al. (2010) found predominantly increasing summer flow. According to the authors, the investigated glaciers until 2004 had still been in a phase of enhanced ice melt contributions to streamflow and the detected trends can be explained by increases in temperature and changes in snow cover. Overall, the results by Pellicciotti et al. (2010) demonstrated that the trends are highly dependent on catchment glacier coverage and the period of analysis resulting in different signs of trend reflecting glacier mass balance changes. Results of trend analyses for partially glacierised catchments by Stahl et al. (2017b) were variable and indicated rather catchment specific patterns. Changes in summer flow of glacierised catchments are more relevant for summer low flow events further downstream than at the scale of the headwater catchments with their summer maximum flow regimes. In contrast, for more pluvially influenced regimes at lower elevations the reviewed studies indicate some tendency to more (but not only) decreasing trends of summer low flows. However, in Switzerland, most rivers integrate runoff over a wide range of elevations and hence the trends depend on a number of runoff generation processes and storages that contribute to different degrees. Apart from a limited ability to attribute the variable trends to their causes, there is a lack of studies on the real extremes beyond the regime components, i.e. changes of seasonal/monthly flow. Among the studies covering Swiss catchments, characteristics based on a specific low flow threshold have been investigated only by Bard et al. (2011; 2015) and Hänggi and Weingartner (2012). The question whether extreme summer low flow events, such as that of 2003, have become more severe or frequent has not been well elucidated by the existing trend studies.

The findings of the studies for Swiss streamflow records are broadly consistent with the reviewed analyses for **regions with similar geographical setting and large-scale studies**. The predominance of increasing winter low flows found for Swiss catchments and for the upper Rhine basin (see Table 3-1) is broadly consistent with results for the wider Alpine and peri-Alpine region for the 1961–2005 period by Bard et al. (2011, 2015). Similarly, regionally coherent patterns of increasing mean flows for the winter months, particularly for catchments with winter-minimum regimes, over the period 1962–2004 emerged in the pan-European study by Stahl et al. (2010). Regarding characteristics of winter low flow timing (start, centre, and end of low flows below the 15% percentile), Bard et al. (2011, 2015) detected no significant trends for the glacially influenced highest elevation regimes but a significant earlier end of winter low flows for many Alpine snowmelt-dominated catchments. This may be related to the outcome of the trend study on snow cover duration characteristics in the Swiss Alps by Klein et al. (2016), which found changes to be more consistent and stronger in spring, i.e. a shift towards earlier snowmelt, than changes towards later snow onset in autumn/winter. Mean flows during summer months (Jun–Aug) have mostly decreased and the AM_7 low flow of the May–Nov period appears to have decreased in magnitude and shifted to an earlier date over the period 1962–2004 for the majority of streamflow records with summer low flow regimes analysed by Stahl et al. (2010). Bard et al. (2011, 2015) note a tendency towards increasing severity of summer low flows in the south-eastern part of their study region, and explicitly for some

Slovenian catchments, however, the results were not quantitatively presented in the publication. For annual mean streamflow changes (1962–2004) across Europe a regionally coherent dipole-like pattern, with decreases in southern and eastern regions and generally increases elsewhere with the Alps (and Switzerland) as the most apparent divide of contrasting streamflow changes, emerged from the study by Stahl et al. (2010). A predominance of decreasing flows for Italian catchments in the Southern Alps found by Bocchiola (2014) may complement and support this continental dipole pattern of historical changes of mean streamflow. More specifically analysing low flows rather than seasonal flows, Renard et al. (2008) and Giuntoli et al. (2012) found trends towards increasing low flow severity for some catchments in southern France. However, analysis results of a few streamflow records from Swiss catchments in the Southern Alpine region (included in Birsan et al., 2005 and Hänggi and Weingartner, 2012) do not support this 'alpine divide' nor do they provide any clear indication towards significant changes in terms of low flows in that region. Targeted low flow trend analyses are generally rather sparse for catchments in southern and eastern Europe. Other reviewed studies covering adjacent regions of Switzerland (see Table 3-1) generally support the predominance of decreasing severity of winter low flows for Alpine/snow-dominated catchments with a winter minimum regime over recent decades but present less consistent and clear changes for summer low flows of more rain dominated catchments. In many other mountain regions of the world long time series are rarely available. Streamflow trend studies for snow-dominated catchments mainly exist from the USA and Canada (e.g. Stahl and Moore, 2006; Luce and Holden, 2009; Déry et al., 2009, Safeeq et al., 2013; Najafi et al., 2017). However, most of these studies also focussed on changed timing of streamflow and declines in summer flow associated with decreased snowpack and glacier retreat rather than explicitly on low flows.

Statistical methods of trend analysis make a number of assumptions on the data structure and have limitations in the interpretation of significances that are discussed for example by Jones (2011), Khaliq et al. (2008, 2009), Viviroli et al. (2012), Safeeq et al. (2013), Merz et al. (2012). In addition, at-site or catchment specific results based on time series of limited length require adequate regionalisation procedures to detect climate change impacts (Renard et al., 2008). Regardless of the statistical significance of results, however, these studies provide the only observation-based analyses of changes. Most of the reviewed studies used streamflow records that were limited to a few decades from ca. 1960 onwards. There is no very recent study that includes data beyond ca. 2010. Methodologically, most studies applied non-parametric or parametric trend tests or simply report on calculated linear monotonic trend lines such as a regression line or the Sen slope (see Table 3-1). As changes in reality are rarely linear and monotonic but often take the form of decadal to multi-decadal fluctuations, one important limitation is the result's dependence on the particular time period analysed (e.g. Giuntoli et al., 2012; Hannaford et al., 2013; Bard et al., 2015). Another limitation of a comparison of different studies into a regional picture of a harmonised low flow trend pattern is the variety of chosen low flow indices (incl. the varying seasonal discretisation).

We would like to point out the value of continued high-quality **streamflow monitoring** and maintenance of existing low flow reference networks (see also Whitfield et al., 2012; Burn et al., 2012) and suggest that these could be used more effectively to monitor ongoing changes in low flows by regular updates of harmonised national trend analyses. Such a monitoring of trends appears important as trend reversals may happen rather quickly if system tipping points are exceeded and processes change (e.g. the peak of the glacier contribution to runoff is passed). Sections 5 and 6 also discuss some of these aspects how process and regime changes may alter low flow characteristics. As for high flow extremes, the frequency quantification of extreme low flows events and also trend analyses of extreme low flows rely heavily on the availability of long time series. Hence, ensuring the continued operation of gauges with near-natural flow and relatively long records should have high priority. In addition, improved availability of appropriate data to quantify the impacts of human activities on streamflow time series in more detail would be needed to foster a progress towards the attribution of detected trends, i.e. to actually test whether climate forcing has been a distinguishable driver of past changes in low flows of the large rivers and the many catchments that are influenced by various water uses (see also Section 6.1). Also several of the streamflow records included in the headwater catchment sample of the reviewed studies here are not completely free of water management influences. Moreover, it should be noted that the less direct, potential effects of land cover changes, apart from retreating glaciers, on (low) streamflow have not at all been considered in the analysis of historical streamflow trends. Jones (2011) criticised that most of recent studies attributed historical trends to climate warming without considering any non-climatic influences, and suggested to rigorously use a checklist of alternative hypotheses including vegetation responses to past disturbances, climate variability, and changes in human water use in the evaluation of streamflow trends.

Take-home messages

- Studies agree that annual winter low flows in Switzerland have predominantly increased across all regions and regimes, as have overall winter streamflows; these increases have been explained by climatic trends and where applicable also by reservoir management with the release of stored water for hydropower production in winter. However, for glacierised catchments at high elevations the results of the reviewed studies are not consistent.
- Studies' results are diverse regarding changes in summer low flows. Trend signals are more heterogeneous, attribution is unclear, and little methodological progress has been made to distinguish climatic and other drivers of change.
- For the scale of Switzerland there are no published studies that included recent streamflow time series for the specific analysis of low flow trends. Available streamflow trend analyses are based on time periods that ended before the year 2010 and explored and discussed mainly changes of seasonal flow and regime shifts.
- Overall, there is an unresolved controversy on trend test methodology, including the chosen statistical tests, underlying assumptions, details of data pre-processing, and how to discern trends from decadal scale variability. Most studies’ records are limited to a few decades from ca. 1960 onwards, hence not including the low flow events of the 1940s.
- These difficulties show the value of continued high-quality long-term streamflow monitoring and low flow reference station networks together with good metadata to allow attribution of causes.

4 Projected changes in low flows from climate change impact modelling studies

Keywords: bias, blocking, calibration, delta-change, downscaling, ensemble, extremes, internal variability, model structure, temporal variability, model chain, parameters, uncertainty cascade, spell length, temporal sequencing

This section reviews the results of latest climate change impact modelling studies. Firstly, the results from modelling efforts in the CCHydro project and findings from recent modelling studies related to low flow events in Switzerland are summarised. In the second part several sources of uncertainties within the hydrological change modelling framework are discussed. Focus is set on those uncertainties that are specifically relevant for the assessment of low flow events in order to characterise the overall capability of current modelling frameworks to project changes in low flows.

4.1 Results of recent climate change impact modelling studies

Results from climate change impact modelling efforts in the CCHydro project and findings from other relevant recent modelling studies related to low flow events in Switzerland are summarised in Table 4-1. The project CCHydro (FOEN, 2012b) studied the effects of climate change on the water balance in Switzerland based on the CH2011 scenarios (CH2011, 2011), which were derived from climate model output from the ENSEMBLES project using the delta-change approach for bias correction and downscaling. Due to this approach, the temporal sequencing including the durations of projected dry spells and meteorological drought periods in CH2011 climate scenarios remained unchanged with respect to the conditions in the reference period. Results **with a specific focus on low flows** are presented in Meyer et al. (2011b) and Meyer (2012). This climate change impact modelling study focused on **summer low flows in the Swiss Plateau region** and used the hydrological model system PREVAH with an extended calibration scheme that incorporated baseflow to achieve a better representation of low flows. Meyer et al. (2011b) analysed the modelled low flow indices Q_{95} (Q_{347}) and AM_7 for May–Oct periods for 29 catchments. They found a clear predominance of decreases of both low flow indices in the model projections across catchments and CH2011 scenario members. However, there was considerable spread among members regarding the magnitude of these decreases and a differentiated confidence in the model projections (Figure 4-1). To evaluate the hydrological model's performance and the corresponding uncertainty of projections in terms of low flows, Meyer et al. (2011b) relied not only on certain quantitative model performance measures but also on the visual inspection of simulated and observed low flows in the reference period, i.e. AM_7, the low flow event of the year 2003, and the period 2002–2004. This semi-quantitative assessment revealed a better low-flow-specific model performance for catchments in the western and central part of the study region than for the peri-alpine catchments in the eastern Swiss Plateau region (see Figure 4-1). Despite the unchanged temporal dynamics of the climate forcing in the CH2011 climate scenarios, results by Meyer et al. (2011b) indicated an increased intensity of summer low flow events with increases in low flow duration and deficit volume. Meyer et al. (2011b) remark that with a better incorporation of changes of temporal variability in climate scenarios and potential increases in future dry spell lengths even more severe summer low flow extremes might be expected in the Swiss Plateau region than implied by their results.

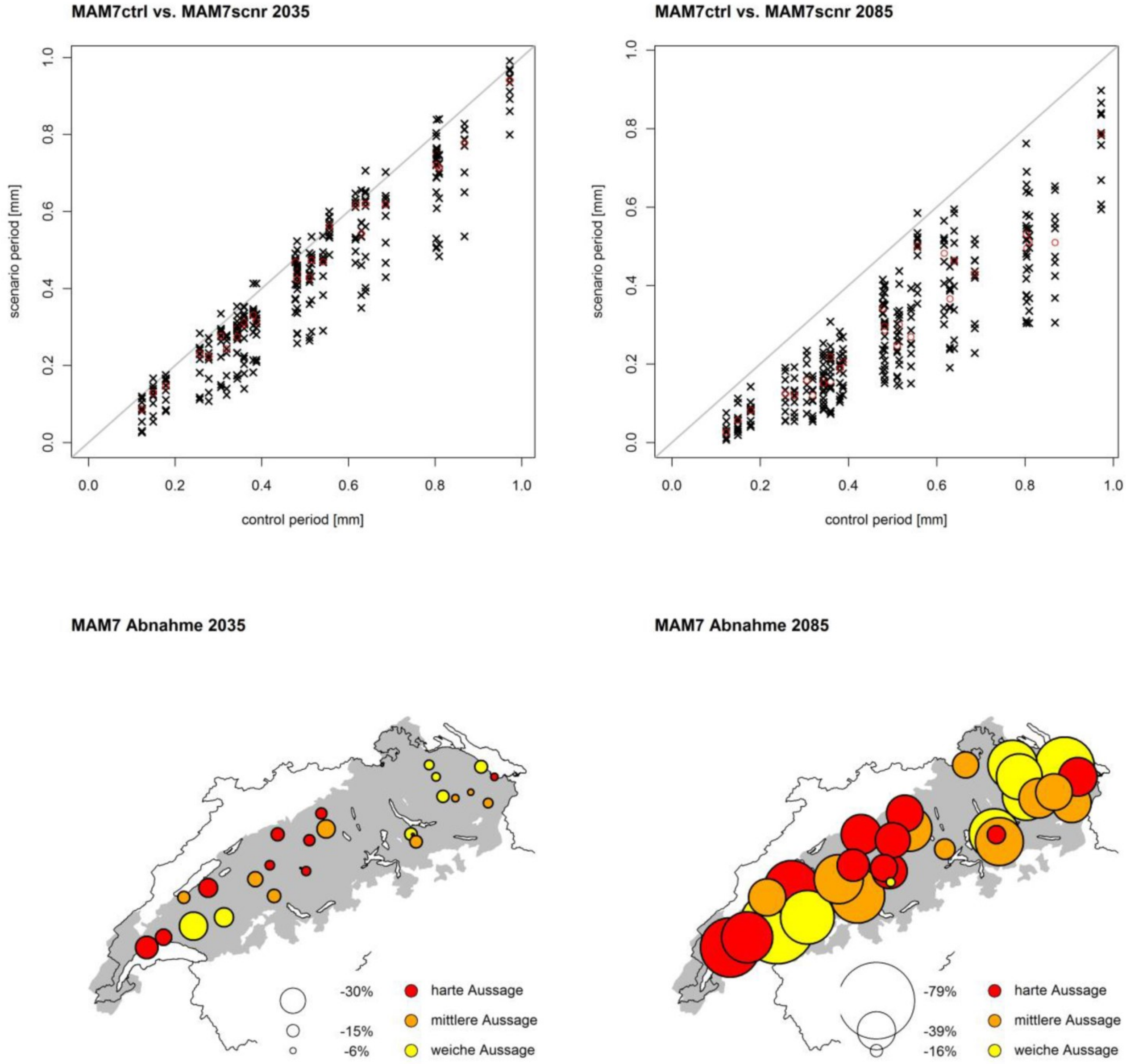


Figure 4-1: Results of the CCHydro study by Meyer et al. (2011b) for projected summer (May–Oct) low flows in catchments across the Swiss Plateau region: projected decrease of mean AM_7 low flow index between the year 1995 and the scenario for the 'near future' time horizon (year 2035, left panel) and the scenario for the 'far future' time horizon (year 2085, right panel). Graph in the upper panel show results from all 10 individual ensemble members with the median marked as red circle. Maps in the lower panel show the ensembles' median values (dot size), colours indicate the confidence in low flow projections based on a semi-quantitative assessment of modelled low flow in the reference period that differentiates three qualitative classes: red: good low flow model performance in the reference period suggesting robust projections (hard facts), orange: fair low flow model performance in the reference period suggesting fairly robust results, and yellow: poor low flow model performance in the reference period suggesting relatively uncertain projections (soft facts). (Figure from Meyer et al. 2011b)

Another CCHydro modelling study conducted modelling experiments for the large river basins of Switzerland (Bernhard and Zappa, 2012). Similar to the majority of all studies, this study was not tailored to address low flow events specifically but rather **projected average changes in the water balance, regimes, and seasonal flows**. However, selected results regarding notable changes of regime minima or low flow indices mentioned for certain catchments are listed in Table 4-1. The CH2011 scenarios with their increases/decreases in winter/summer precipitation and warming induced changes in the modelled snowpack storage, for some rivers such as Aare and Rhine led to a projected future shift from a regime dominated by a winter minimum to a regime dominated by a summer minimum (see also Section 4). According to Bernhard and Zappa (2012) winter will remain the low flow season in all alpine catchments until the end of the 21st century despite projected increases of winter flows. At the large basin scale, however, the relevance of summer low flows may increase. For instance, summer flows of the Rhine at Rekingen were projected to decrease to levels distinctly lower than winter minima of the past.

Overall, the results of the reviewed impact projection studies are broadly consistent. The results also largely agree with results of the analyses of past streamflow time series described in the previous section, namely flow increases in winter suggesting a decreasing relevance of winter low flows for alpine regimes and tendencies for decreases in summer/autumn. Furthermore, all studies consistently found stronger impacts for the 2nd half of the 21st century than for the near future. Nevertheless, some results differ. For instance, one regional catchment cluster (Jura mountains and Swiss Plateau) was considered rather insensitive to climate change by Köplin et al. (2012), whereas Meyer et al. (2011a), who focused on low flows specifically, suggested a considerable vulnerability to low flows for catchments in this particular region. It is important to stress that all findings of studies based on the CH2011 scenarios, including all efforts to assess catchments' sensitivity to climate change at the scale of Switzerland by Köplin et al. (2010, 2011, 2012, 2014), consider only changes with respect to the mean annual cycle. The delta-change approach used for the generation of the CH2011 scenarios is an efficient way for investigating mean climatological and hydrological changes. However, for the analysis of potential future changes in low flow events, the **missing consideration of changes in the year-to-year and day-to-day climate variability in scenarios** was a major limitation on top of many considerable uncertainty sources for projections of extremes, as detailed in the next subsection. The new CH2018 scenarios are expected to allow a more detailed analysis of changes in extremes.

Notable **other limitations** in the reviewed studies include missing or strongly simplified representations of glacier retreat and water management operations in the models. Whereas glacier geometry changes were not yet incorporated explicitly in modelling within the CCHydro project, since then many hydrological models have implemented solutions to account for transient glacier retreat. Most of the modelling studies covering the large river basins (lower part of Table 4-1) incorporated known major water management operations such as reservoirs and diversions somehow. However, uncertainties remain related to water management operations that were neglected in the models, are less evident/unknown, or cannot be described sufficiently in an explicit quantitative manner (also see Section 6.1). Moreover, it is a common practice to assume unchanged management rules in scenario periods.

Table 4-1 Summary of reviewed climate change impact modelling studies for catchments in Switzerland with respect to findings relevant for low flows.

Reference	Catchments / regions	Climate scenarios	Hydro model(s)	Findings and authors' conclusions
*Climate change impact modelling studies for Swiss catchments within **CCHydro project** including results for **changes of low flow indices***				
Bernhard & Zappa (2012)	**Large basins** covering **Switzerland**	CH2011$^{1)}$ local-daily (A1B emission sc.) selection of representative stations and internal interpolation	PREVAH-WSL calibration criteria: volume error, NSE, NSE for ln(Q); parameter regionalisation for ungauged areas based on Viviroli et al. (2009) / Köplin et al. (2010)	Winter remains the low flow season in alpine catchments with a tendency of increased minima. Average flows and **low flows in summer expected to decrease**. Especially in the Swiss Plateau region summer low flows expected to become more severe also due to time shifts of the snowmelt season (higher snow line altitude). Overall, for many large basins **combined effects result in a higher relevance of future summer low flows**, which may reach lower levels than winter flow minima in the ref. period (1980–2009). Selected results: • 2070–2099 scenarios' tendency for regional decreases in precipitation reflected in **overall streamflow decreases in the** catchments of **Saane, Sense, Gürbe**, **Thunersee,** and in the **Ticino** region. • Distinct **decreases of summer (low) flows:** Ill, Thur, Glatt, Töss, Broye, Emme, Sense, Saane, Lago Maggiore, and Tresa. • **Transition** from a regime with intra-annual winter flow minimum **to dominant summer flow minimum**: Linth, Kleine Emme, Aare (gauge Untersiggenthal), and Rhine. • Emergence or intensification of **secondary flow minima in summer for** Reuss@Seedorf and Ticino@Bellinzona with projections' ranges for future winter and summer minima flow level overlapping. • Explicitly reported **decreases in Q_{95}** (Q_{347}) projected by the majority of ensemble members: Rhine@Rekingen (up to -20% compared to ref.), Limmat (up to -20%), Sense (-10 to -50%), and Ticino@Bellinzona (-5 to -25%). • **Decreases of Q_{90} among large basins**: Limmat@Baden, Rhine (gauges Basel and Neuhausen), and Aare (gauges Brugg and Untersiggenthal).
Meyer et al. (2011b); Meyer (2012)	**Swiss Plateau**, 29 mesoscale catchments	CH2011$^{1)}$ daily-local (A1B emission sc.) delta-change signal of one representative station applied to gridded data (MeteoSwiss)	PREVAH-GIUB calibration criteria: volume error, NSE, NSE for ln(Q), additionally calibrated to baseflow	For the analysed catchments in the Swiss Plateau region with their characteristic summer flow regime minimum **consistently projected decreases of both low flow indices, Q_{95}** (Q_{347}) **and summer AM_7**. Consequently**, low flow duration and deficit volume expected to increase**, using the reference period's Q_{95} or AM_7 as threshold. In particular in the central and western parts, an increase of periods with flow below the reference Q_{95} by 12 days on average are considered likely. Generally, the projected changes are moderate for the 2021–50 and more severe for the 2070–99 scenarios, which imply distinct decreases of summer precipitation. Based on a semi-quantitative assessment of the model's performance with respect to the representation of low flow events in the ref. period, confidence in projected low flows for perialpine catchments in the eastern part of the region considered lower than for other catchments.

Reference	Catchments / regions	Climate scenarios	Hydro model(s)	Findings and authors’ conclusions
CCHydro project and follow-up studies**, presenting **changes in seasonal mean flow (regime),** i.e. **no targeted exploration of low flows				
Köplin et al. (2010, 2011, 2012, 2014)	189 mesoscale catchments across **Switzerland** → clusters and representative case study catchments	CH2011[1] daily-local (A1B emission sc.) daily delta-change signal applied to stations’ hourly data and internal interpolation	PREVAH-GIUB calibration criteria: volume error, NSE, NSE for ln(Q)	Cluster analysis to classify the catchments to types of similar hydrological response to climate change. With only one exception all clusters exhibit clearly **decreases in summer flow and increases in winter flow**, particularly evident for the ‘far future’ period (2074–95). **Decreases in summer flows are generally a result of decreases in summer precipitation and increased ET**. For snow-dominated catchments decreases in summer amplified due to decreased melt. Note: one regional cluster (Jura mountains and Swiss Plateau) considered rather insensitive to climate change here, whereas Meyer et al. (2011) expected a considerable vulnerability to low flows for catchments in this region!
Rössler et al. (2014)	Six mesoscale catchments in Switzerland: **Rhône, Vorderrhein, Verzasca, Emme, Thur, Venoge**	Extended CH2011[2] daily-local and daily-regional (A1B, A2, RCP3PD emission scenarios)	HBV-light, PREVAH-GIUB, PREVAH-WSL, WaSiM-ETH	Despite differences of the hydrological models and a large spread between scenarios and models, **principal climate change response patterns by Köplin et al. (2012) confirmed** with the **sign of the projected changes remaining consistent among all model chains**. Dependent on the greenhouse gas scenario the projected changes in summer flow differed by about a factor of 2.
Addor et al. (2014)			HBV-light, PREVAH-GIUB, WaSiM-ETH	Major findings regarding hydrological change see Rössler et al. (2014). In addition, a comprehensive **systematic assessment of different uncertainty sources** is presented.
Milano et al. (2015b)	Nine mesoscale catchments in the canton of **Vaud**: **Promenthouse, Aubonne, Venoge, NozonTalent, Mentue, Broye, Grande Eau, Sarine**	CH2011[1] (A1B emission sc.)	PREVAH-GIUB calibration criteria: volume error, NSE, NSE for ln(Q)	All scenarios for 2050–71 agree on **decreases in summer flow**, especially for pluvial regimes in the Swiss Plateau region, for which the decrease is attributed to increasing temperatures and decreasing summer precipitation. For alpine areas hardly changes in precipitation projected but a decrease in snow accumulation leading to a shift in flow seasonality.
Milano et al. (2015a)		CH2011[1] daily-local (A1B emission sc.) only two (most pessimistic / optimistic) sc. combined with sc. on population growth and water needs		**Under both climatic and anthropogenic change scenarios, moderate water stress could occur from May to Sep**. **Under the worst-case scenario, severe water stress concentrated mainly in summer** but could occur even from May to Aug in the Venoge and Talent catchments. Study considered streamflow as the only available freshwater resource, even though in reality other supply sources (groundwater and lakes) are used. This assumption causes the largest uncertainty and may partly lead to an overestimation of the water stress situation.
Jenicek et al. (2018)	14 mesoscale catchments in Switzerland (mean elevations: 845–2368 m a.s.l.)	CH2011[1] daily-regional (A1B, A2, RCP3PD emission scenarios) mean of scenarios used	HBV-light calibration criteria: NSE, volume error, MARE, efficiency for SWE	Distinct **overall decreases in summer flow for all studied catchments,** with the largest changes for the highest-elevation ones, and also decreases in ‘summer low flows’ represented by the 7-day minimum flow analysed separately for each month (Jun–Aug). Main objective was to explore the **influence of snow changes, i.e. decreasing amount and melt season shift to earlier spring, on summer (low) flows**: In the ref. period the influence of snow on summer flow rather minor for lower elevation catchments, increased with mean elevation. For the scenario periods this influence progressively reduced. Decreases in summer flow were related to combined effects of decreasing snowmelt contributions, decreases in precipitation, and increases in actual ET. The influence of precipitation and ET appear more important for lower compared to higher elevation catchments, where the influence of snow on summer flow is more evident.

Reference	Catchments / regions	Climate scenarios	Hydro model(s)	Findings and authors' conclusions
*Studies for **large rivers** with headwaters in Switzerland*				
Fatichi et al. (2014)	**Upper Rhône and upper Po** basins	3 scenarios with GCM: ECHAM, RCMs: REMO, RegCM3, (A1B emission sc.) stochastic downscaling and non-linear parametric bias correction	Topkapi-ETH	**Streamflow natural variability likely larger than the projected climate change signal by the mid-21st century** in most stream sections. For fdc of the **river sections** of the Po and Stura, both **with a summer minimum regime, consistently sig. departures from the control projected with a decrease in summer low flows**. **Expected reductions in ice melt contributions may affect late summer flow at the** entire upper Rhône and Po **basin scale**.
Fatichi et al. (2015)	**Upper Rhône** basin			In addition to Fatichi et al. (2014), spatially-distributed **changes in daily minimum flow** between ref. and scenario period 2041–50 presented **with predominantly small changes** but by up to +60/-60% for individual headwater sections. I**nfluence of hydraulic infrastructures buffers climate variability** to a certain extent, inhibiting esp. detection of low to medium flow variability downstream.
Krahe et al., 2011; Bernhard et al., 2011	**Alpine Rhine** basin (gauge Diepoldsau)	20 scenarios from ENSEMBLES dataset out of which: 8 used by all hydro models and 10 analysed in detail 3 downscaling methods: delta-change, linear scaling, quantile-mapping	HBV 134, PREVAH-IAC, PREVAH-WSL	Model chains agree largely on only marginal changes of annual flow in the near future, whereas a **tendency towards lower mean flows** is clearer **for 2071–2100** scenarios. Projected seasonal mean flows clearly show **increases for Nov to Feb**. Projected **summer flow reveals a decrease** by up to -50%. Analysed low flow index: AM_{31}. All 77 projections agreed on increases in AM_{31} for both periods, ranging from negligible up to >+60%. Remarks: Long-term mean of AM_{31} closely linked to regime minimum, which may shift from a winter to a summer low flow regime at Diepoldsau (inconclusive results). This and reservoirs' impact to be considered when interpreting changes of this index.
Görgen et al. (2010) [3]	**Rhine River basin** upstream of Lobith	20 scenarios from ENSEMBLES dataset downscaling based on simple linear scaling (per month correction factors)	HBV 134	Results for projected low flows presented only for Rhine gauges with Basel the only one in Switzerland. Analysed low flow indices for the 30-yr ref. and scenarios periods: i) Q_{90} and ii) AM_7 calculated for both, summer (May–Oct) and winter (Nov–Apr). Generally for gauges along the Rhine: no clear tendency in summer and increases in winter low flows for the 2021–50 scenarios. **For 2071–2100 a stronger change signal is projected for summer, with a tendency towards decreased low flows**.
Demirel et al. (2013c)	**Rhine River basin** upstream of Lobith	7 GCM–RCM scenarios (A1b, A2, B2 emission sc.) downscaling see Görgen et al. (2010)	HBV 134 calibration criteria: volume error, NSE, NSE for ln(Q)	**Considerable deviations of seasonality indices based on obs. and sim. low flows**. Esp. **large uncertainties for alpine tributaries** maybe partly due to the missing model representation of lake and reservoirs. High sensitivity of low flow seasonality indices to climate model; RCMs/GCMs influence on low flow timing larger than that of emission scenario. However, according to climate projections for 2063–98 substantial change in low flow seasonality index expected, **for two alpine tributaries a regime shift from winter to summer low flows likely.**

[1] See CH2011 (2011); Bosshard et al. (2011a, 2011b); von Waldow et al. (2014)

[2] See von Waldow et al. (2014); Fischer et al. (2012)

[3] Note the published erratum, which refers to the projections for Q_{90} low flows, see: http://www.chr-khr.org/sites/default/files/chrpublications/rapport_i_-_23_erratum_2011-11-03_0.pdf

Abbreviations: ET: evapotranspiration, GCM: general circulation model or global climate model, NSE: Nash-Sutcliffe efficiency, RCM: regional climate model, RCP: representative concentration pathway.

4.2 Uncertainty sources and limitations of climate change impact modelling frameworks from a low flow events perspective

The use of a **climate–hydrology modelling chain** in scenario-led impact studies is a standard way for assessing future changes in hydrology. The main elements of such modelling chains are typically one or several greenhouse gas emission scenarios, an ensemble of climate model simulations, post-processing of climate model output, and one or several hydrological models. Each step in the chain entails a main source of uncertainty (Figure 4-2) and should be evaluated for suitability with respect to low flow representation in particular. In climate modelling, a prevailing principle to address uncertainties is an ensemble approach, i.e. the use of several combinations of emission scenarios, climate models, and post-processing. In contrast, in hydrological impact studies the use of several hydrological models at the catchment scale (Bosshard et al., 2013; Velázquez et al., 2013; Rössler et al., 2014; Addor et al. 2014; Gosling et al., 2017; Krysanova et al., 2018; Melsen et al., 2018) has not become a standard yet. The majority of hydrological impact studies have relied on only one hydrological model, for which often, but not always, realisations for different parametrisations characterise parameter uncertainty.

It is undisputed that overall uncertainties of climate impact projections are large and that none of the uncertainty sources nor interactions among them should be neglected a priori. However, in hydrological impact studies some of these sources have often been overlooked or neglected, especially, uncertainties linked to internal climate system variability and hydrological modelling (Clark et al., 2016). Studies that address **sources of uncertainties** specifically **for low flow projections** (Wilby and Harris, 2006; Forzieri et al., 2014; Vidal et al. 2016; Parajka et al., 2016) are even less frequent.

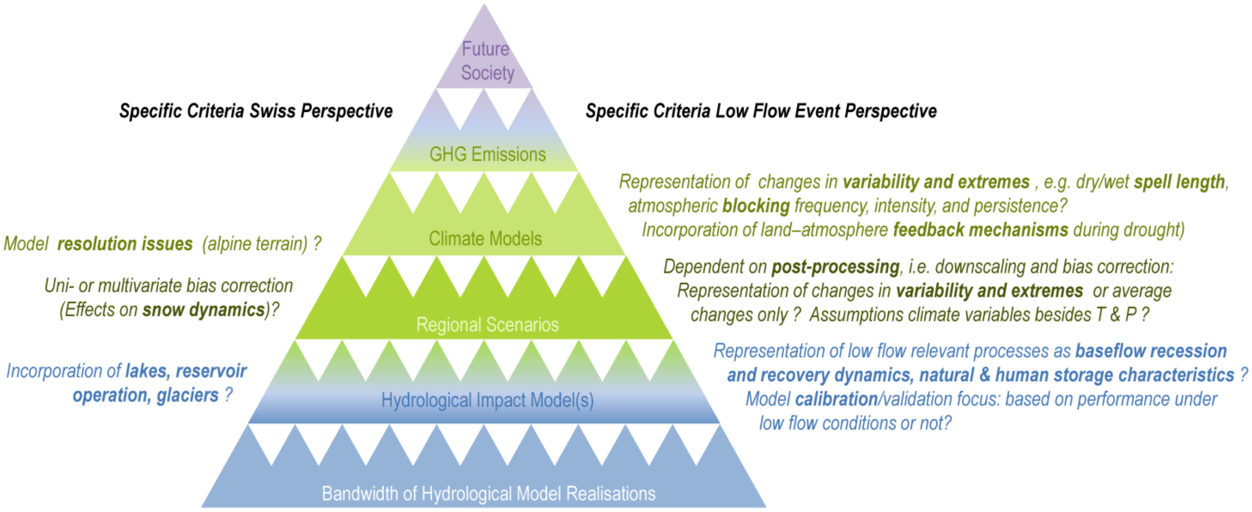


Figure 4-2: A cascade of uncertainty proceeds from different socio-economic and demographic pathways and their translation into greenhouse gas (GHG) emissions, global and regional climate models' output, and impacts—here impacts on hydrology (adapted from Wilby and Dessai, 2010). The resulting envelope of uncertainties, i.e. the bandwidth of realisations, reflects the number of permutations at each level and the parametric uncertainty of the applied hydrological model(s). Specific questions are added pertaining to low flow changes in Switzerland.

It should be noted that the spread of an ensemble's outcomes, as illustrated in Figure 4-2, does not necessarily cover the full range of uncertainty arising from internal climate variability or limitations of the used modelling tools and techniques, such as remaining model biases, structural model errors or neglecting part of the potential physical changes in the studied catchment which may lead to changed system functioning (instability of model parameters, crossed tipping points). In light of a strong influence of model experimental design, Dessai and Hulme (2004) caution about the danger to misinterpret ensemble projections as actual probabilities. This section does not cover all aspects of climate change impact modelling uncertainty comprehensively, but points out some issues that should be kept in mind when interpreting results of impact modelling from a low flow event perspective. Most important, studies tailored to project low flows clearly are to be treated as distinct from studies that do not. The numerous decisions and methodological choices during the setup of a study-specific modelling chain are highly dependent upon the key questions formulated. Hence, any low flow projections resulting as a byproduct from impact modelling studies that were designed mainly to adress other aspects or rather use “ad hoc ensembles of opportunity”, as phrased by Clark et al. (2016), have to be regarded critically.

Despite continuous efforts in research and model development, the outputs of global and nested regional **climate models** are in general biased and subject to large uncertainties. For low flow, due to its nature as an extreme event and driving processes (Section 2), specific aspects of climate forcing need to be considered. Consequently, uncertainties arising from climate models that may be particularly relevant for low flow impact projections for Swiss catchments are related to: limitations in the representation of climate extremes, anomalies, dry spells and meteorological droughts, heat waves, and cold waves, the incorporation of land-surface–atmosphere feedback mechanisms, and internal climate variability. Reviews and discussions on the confidence in and the **uncertainty of current climate models' projections of climate extremes and drought** can be found among others in Fowler et al. (2007), CH2011 (2011), IPCC (2012), Orlowsky and Seneviratne (2013), Zwiers et al. (2013), Fischer et al. (2013), Nicholls and Seneviratne (2015), Moon et al. (2018), and in the Hydro-CH2018 contribution on soil moisture and evapotranspiration. Besides definitional issues and lack of observational data, the inability of climate models to include all the factors influencing droughts precluded stronger confidence than ‘medium’ in drought projections in the IPCC's SREX and AR5 reports (Seneviratne et al., 2012). Key reasons of uncertainty for projections of drought, dry spells, heat waves, and cold waves have been suggested to be linked to circulation changes and the strength of land-surface–atmosphere interactions (CH2011, 2011; Orlowsky and Seneviratne, 2013).

As mentioned in Section 2, extreme weather situations, as cold spells or dry spells, in mid-latitude regions are caused by persistent anticyclonic pressure systems, frequently linked to atmospheric **blocking** patterns. The future evolution of blocking events' location and frequency is crucial for understanding regional climate change with respect to extreme conditions (Christensen et al., 2013). The latest generations of general circulation models (CMIP3 and CMIP5 models) are known to underestimate blocking frequency and persistence (CH2011, 2011; Christensen et al., 2013; Zwiers et al., 2013; Masato et al., 2013). Especially many climate models still have severe problems in simulating the northern hemisphere blocking activity in the North Atlantic that causes climate anomalies over large parts of Europe. CMIP5 models generally underestimate the observed occurrence of blocking over the Euro-Atlantic sector with considerable inter-model spread and future trends are highly unclear (Christensen et al., 2013). An analysis of CMIP5 simulations by Wetter et al. (2014) suggests that state-of-the-art climate models are so far unable to simulate events of the severity as that of the

European megadrought of 1540. Even with considerable improvements of climate models, impact studies for extremes will remain challenging as a result of large irreducible uncertainties on local to regional scales because of **internal (unforced) climate variability** (Fischer et al., 2013; Addor and Fischer, 2015; Hakala et al., in print). Orlowsky and Seneviratne (2013) found large uncertainty contributions of internal climate variability for projections of drought. Hydrological impact projection studies found a considerable role of internal variability for overall uncertainties (Fatichi et al., 2014; Vidal et al. 2016), and several other recent studies have revealed that uncertainties associated with internal climate variability have often been neglected or underestimated (Clark et al., 2016).

For the hydrology in Switzerland, uncertainty and biases of climate model output is particularly challenging due to the orographically complex terrain and pronounced climate variability that is complicated by the transition between Atlantic and Mediterranean climate conditions (Viviroli et al., 2011). Mountain environments emphasise **issues of model resolution** and the need of appropriate **post-processing** techniques, i.e. **downscaling and bias correction** approaches, for creating **regional scenarios,** which are required as input for a hydrological impact model. Whereas the CH2011 scenarios are based on the delta-change approach, the CH2018 scenarios are based on a quantile mapping technique (CH2018, 2018; Feigenwinter et al., 2018). Although associated with many caveats and limitations (see e.g. Ehret et al., 2012; Addor and Seibert, 2014; Maraun, 2013, 2016; Clark et al., 2016; Takayabu et al., 2016; Maraun et al., 2017), post-processing of climate model output including ‘bias correction’, or ‘bias adjustment’, is widely used and considered an indispensable part of hydrological impact modelling. It is well established that bias correction leaves inconsistencies in the post-processed time series and can only improve selected aspects of climate simulations (Addor et al., 2016). Hence, selection of techniques should assess specific aspects depending on the intended impact application. For instance, perturbation techniques such as the **delta-change approach** can be a robust approach for the investigation of changes in long-term average values but have clear limitations for any assessment of changes in climate variability and extremes (Fowler et al., 2007; Bosshard et al., 2011b; CH2011, 2011; Teutschbein and Seibert, 2012; Vormoor et al., 2017). The delta-change approach produces climate scenarios by applying differences between control and future climate model simulations in form of mean change factors to baseline observations. Thereby, changes in temporal and spatial variability of climate are disregarded; following the delta-change approach the temporal sequencing of the control period time series is retained, excluding among others changes in wet and dry spells.

Temporal sequencing of the climate forcing eventually used as input data is one of the aspects particularly important for hydrological applications, and especially assessments of changes in anomalies and extremes, i.e. high and low flows. Vormoor et al. (2017) tested the influence of changes in the temporal structure represented by different climate input for four streamflow indices: mean flow, annual maximum flow, the low flow index AM_7 for May–Sep periods, and a flow seasonality index. Their results suggest that the effect of changed temporal structures is minor for mean flows but considerably affects high and low flows with the overall largest influence on the low flow index. An Australian study demonstrates that altered sequencing preceding and during a low flow event can have a significant impact on ecological conditions and consequences (Wang et al., 2018). The crucial role of temporal sequencing in the applied bias correction method has been often overlooked in impact studies. Addor and Seibert (2014) question whether the bias correction performed on daily data is adequate for hydrological studies. Whereas Addor and Seibert (2014) found large remaining biases in multiday and interannual statistics after correcting daily climate data based on quantile mapping, other studies concluded that, even though not explicitly forced in the algorithm, quantile mapping can substantially improve temporal statistics, such as (wet and dry) spell lengths (Rajczak et al., 2016; Ivanov and Kotlarski, 2017). In conclusion, hydrological impact modellers should be aware that the choice of bias correction algorithm sets the state of ''knobs'' that control whether distributions, intervariable or spatial dependence structure, and temporal sequencing are informed more by the climate model or historical observation data (Cannon, 2016). A method that better reproduces the historically observed temporal structure may increase the confidence in hydrological projections in particular with respect to low flow events. On the other hand, modifications of temporal, spatial, or variable interdependence structures risk major consistency breaks with the driving climate models (Maraun et al., 2017).

Vidal et al. (2016) have presented the most comprehensive assessment of uncertainty sources in hydrological impact modelling dedicated to low flow projections so far. In their study for two snow-dominated catchments in France an ensemble built from multiple climate models, three statistical downscaling methods, and six hydrological models was used in combination with approaches to account for internal variability (Figure 4-3). In this study the fraction of the explained variance explained by the three statistical downscaling methods, was found to be small compared to other uncertainty sources. General conclusions on the uncertainty contribution of the downscaling step were impossible due to a potentially limited representativeness of the three employed methods, which all belong to the family of perfect prognosis methods (Vidal et al., 2016).

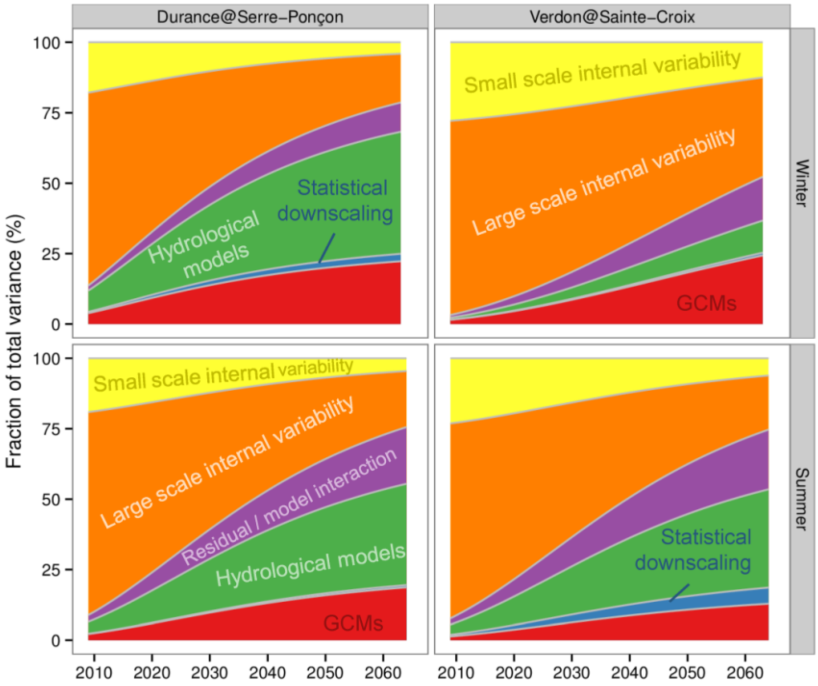


Figure 4-3: Uncertainties of projected low flow changes (30-year rolling averages of changes in AM_7 compared to reference) from the study by Vidal et al. (2016, graph slightly modified): Fraction of total variance explained by each source of uncertainty: red: four general circulation models (GCMs), blue: three statistical downscaling approaches, green: six hydrological models, purple: residual/model interaction uncertainty, orange: large scale internal variability (originating from GCM output), and yellow: small scale internal variability (originating here from different stochastic realisations of statistical downscaling).

Besides overall dominating contributions of internal variability that largely masked the change signal in low flows, an important finding by Vidal et al. (2016) was the considerable contribution of **uncertainty originating from the hydrological models.** This uncertainty contribution was even larger than that resulting from the four different general circulation models. The diverging low flow responses to climate change projection from the different hydrological models presumably are a result of differences in the implemented evapotranspiration and snowpack approaches (Vidal et al., 2016). In this respect results by Vidal et al. (2016) are consistent with a high relevance of uncertainty contributions from hydrological models found for snow-dominated catchments in other studies (Addor et al., 2014; Parajka et al. 2016). It has been a prevailing perception that climate uncertainty dominates hydrological impact studies, but recently an increasing number of studies (e.g. Bastola et al., 2011; Velázquez et al., 2013; Vaze et al., 2010; Honti et al. 2014; Mendoza et al., 2015, 2016; Fowler et al., 2018) have stressed that subjective choices in the **selection of hydrologic model structures and parameters** can substantially influence the portrayal of climate change impact. Particularly, in terms of baseflow and low flow several studies found large discrepancies between hydrological model outputs (Velázquez et al., 2013; Mendoza et al., 2015).

How well do typical conceptual hydrological models, which are commonly used for climate change assessments but that were traditionally calibrated mostly to meet the rainfall–runoff response, capture processes that control streamflow during low flow? This question is closely linked to the **representation of catchment storage characteristics in the model structure** (see also Section 6) **and their parametrisation by calibration**. For instance, hydrological models still predominantly use the linear reservoir algorithm to model streamflow recession, while among others Wittenberg (1999) claimed that considering nonlinearities of storage effects would often better reflect reality over longer time ranges. Santos et al. (2018) found that for Swiss catchments with summer low flow regime and for karstic catchments the description of summer flows strongly benefits from using a nonlinear storage–discharge relationship. Kirchner (2009) proposed to derive the **storage–outflow relationship** and a catchment's dynamic storage from streamflow observations, instead of specifying this relationship a priori as done by the aplication of conceptual models with fixed structure. Teuling et al. (2010) found that the behaviour of the Rietholzbach catchment in the Swiss Plateau region under wet conditions does correspond to that of a simple dynamical system, whereas under dry conditions (rare low flows) the estimation of storage and the functional relationship becomes highly uncertain.

Stoelzle et al. (2015b) systematically evaluated different groundwater model boxes as storage–outflow model structures for catchments in south-western Germany, covering a wide range of hydrogeological characteristics, to identify appropriate model structures for baseflow simulation in relation to the geological settings. The simplest structures tested revealed clear limitations in representing baseflow and low flow behaviour compared to more versatile structures, including in particular such allowing for groundwater leakage, concurrent faster and slower flow paths, a representation of short- and long-term recession behavior, or threshold-controlled storage depletion dynamics. Overall, the selective strengths and weaknesses in the representation of baseflow call for a wider consideration of more flexible conceptual groundwater model structures in hydrological models, which would allow applications more specific for the purpose and the modelled catchment aquifer system (Stoelzle et al., 2015b). Moeck et al. (2016) criticise that hardly any of the numerous climate impact change modelling and uncertainty studies have considered the uncertainty of simulated recharge under climate change caused by the **hydrogeological model conceptualisation** and **model biases due to**

calibration strategies not suited for low flow simulation (e.g. focused on high flows) or/and calibration periods that lack extreme weather conditions.

Compared to flood forecasting low flow events have received limited attention in hydrological modelling for a long time, but recent events and environmental flow regulations may have fostered increasing efforts. General limitations in the low flow performance of hydrological models and calibration strategies have been investigated in numerous studies over the last few years (Meyer et al., 2011a; Pushpalatha et al., 2012; Demirel et al., 2013b; Pfannerstill et al., 2014; Nicolle et al., 2014; Staudinger and Seibert, 2014; Tian et al., 2014; Willems et al., 2014; Stoelzle et al. 2015b; Parajka et al., 2016; Saft et al., 2016; Fowler et al., 2018). Most of the models used in hydrological impact assessments at the catchment scale rely heavily on **parameter identification through model calibration** over a reference period. Here, it should be noted that some of the studies that found a high intermodel spread in low flow simulations referred to above (Velázquez et al., 2013; Mendoza et al., 2015; Vidal et al., 2016) are based on a **model calibration strategy** that did not explicitly consider the objective of low flow simulation. It is still common among modellers to judge on performance solely based on the numerical value of some **goodness-of-fit measures** and the Nash–Sutcliffe is still widely used (Seibert et al., 2018). Many of the ('least-square-type') **objective functions** commonly used in hydrological model calibration focus on the high flow response and tend to emphasise wet days/years, whereas projections of future droughts, low flows, or a generally drying climate may require to optimise hydrological model parameters based on objective functions that enable a more balanced consideration of the flow regime or even targeting very low flow conditions (e.g. Pushpalatha et al., 2012; Fowler et al. 2018).

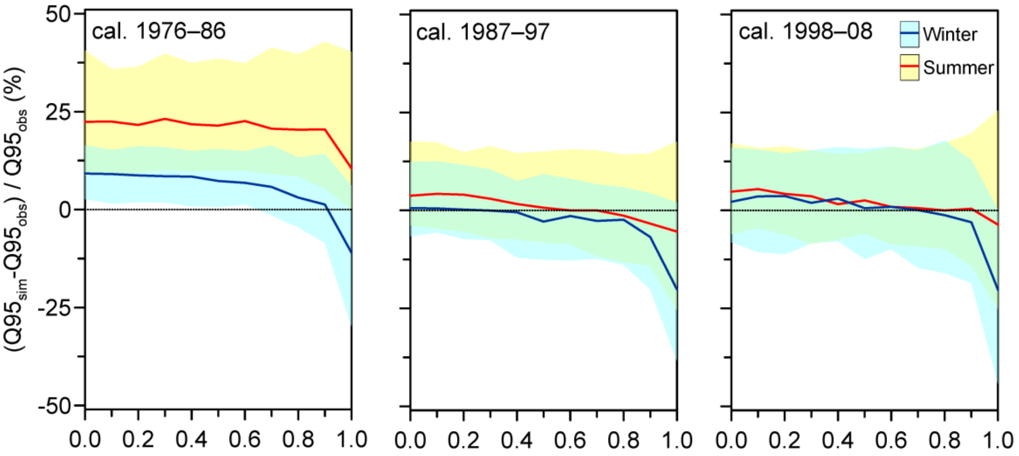


Figure 4-4: Results of the study by Parajka et al. (2016) for 262 catchments across Austria: difference between simulated and observed Q_{95} low flow for three different calibration periods (left, centre, right) and different calibration variants (x-axis) based on an weighted objective function consisting of two variants of the Nash–Sutcliffe efficiency, namely the standard one that focusses on high flows and the version calculated on log transformed flow less focussed on high flows; the eleven calibration variants were realised by varying the weighting w_Q (x-axis) of both criteria between 0 and 1 with $w_Q = 0$ corresponding to a calibration using only the Nash–Sutcliffe efficiency calculated on log transformed flow and $w_Q = 1$ corresponding to using only the standard variant. Lines represent the median, scatter (i.e. 75–25 % percentiles) show the variability over catchments with dominant winter (blue) and summer (yellow) low flow regime. The differences are estimated between simulations and observations of Q_{95} in the entire reference period 1976–2008.

Parajka et al. (2016) tested the effects of differing calibration variants and calibration periods on the uncertainty of Q95 low flow values in historical simulations and projections for climate scenarios based on the delta-change approach for catchments across Austria. They found that the simulated Q95 may vary up to 60% depending on the decade and the objective func-tion used for calibrations. Figure 4 4 shows that a clear difference is found especially for the calibration variant based solely on the standard Nash–Sutcliffe efficiency versus all other variants that included the Nash–Sutcliffe efficiency calculated on log transformed streamflow with variable weighting. Overall, the results clearly indicate the importance of the selected objective function in hydrological model calibration for low flow projections.

A considerable effect of the **calibration period** on the uncertainty of hydrological model parametrisation was found by several studies. The time stability of model parameter sets, i.e. their transferability to changed climate conditions, is an intensively discussed aspect of hydrological impact assessments in general (e.g. Vaze et al., 2010; Merz et al., 2011; Coron et al., 2012; Kling et al., 2015; Saft et al., 2016) and especially relevant for assessments for hydrological extremes. To obtain robust parameters for low flow projections the period for model calibration should be sufficiently long and capture a wide range of historical variability including in particular extreme drought and low flow events; the used objective functions should, if not focussed on low flows, at least not lead to model parametrisation biases in favor of high flow performance. To judge the capability of a calibrated model to project future low flow events for a specific catchment an assessment of the low flow model performance including the visual inspection of simulated hydrographs for historical low flow events, as realised by Meyer et al., (2011b), might be more instructive than just relying on values of certain goodness-of-fit metrics. Nevertheless, the incorporation of hydrological parameter uncertainty should be a standard in impact assessments to avoid an over-confident portrayal of climate change impacts (Mendoza et al., 2016; Seibert and van Meerveld 2016).

In summary, a general limitation of previous Swiss climate impact modelling studies was the strongly impeded possibility for assessments of extremes based on the CH2011 climate scenarios. This was a major gap to users and should be better addressed in the generation of the new CH2018 scenarios (MeteoSchweiz, 2016). Since then, issues of bias correction for hydrological modelling have been further explored. To inform the selection of appropriate bias correction methods, Addor and Seibert (2014) suggest more efforts into the systematic exploration of the consequences of bias correction methods on hydrological projections: studies should directly investigate the effects of different approaches or bias corrected vs. non bias corrected data directly in hydrological impact modelling. A study for two alpine catchments in Switzerland demonstrates that conclusions drawn from impact studies that apply a bivariate bias correction of temperature and precipitation can differ from those based on univariate bias correction (Meyer et al., 2018); this finding is mainly a consequence of rain–snowfall partitioning simulations that differ between uni- and bivariate bias correction and may be particularly relevant for hydrological impact modelling in Switzerland with its many snow-dominated catchments. Further gaps to the interpretability of projected low flow changes from previous model-chain studies were limited incorporation of glacier geometry changes, present-day and future water management operations, and missing incorporation of land cover feedback to climate change. All these aspects are relevant not only for low flow events and are partly addressed in ongoing projects.

Overall, uncertainties for low flow projections are large. With the known challenges these uncertainties may not be substantially reduced. Therefore a thorough assessment of potential future low flow changes requires i) comprehensive assessments of the uncertainty in traditional model chain scenario experiments and ii) alternative bottom-up approaches. Traditional scenario-led assessments may aim for a more structured reduction of uncertainties before/during ensemble building as recommended by Clark et al. (2016) and depending on the objective of low flow assessment. Excluding inappropriate models/methods from a low flow event perspective would likely reduce many ensembles. A comprehensive characterisation of all uncertainty sources as was done by Vidal et al. (2016) could become a standard way of characterisation. In light of the large remaining uncertainties and limitations that contrast stakeholder information demands, several researchers from the hydrological and the climatological communities advocate that in parallel to conventional scenarios, complementary approaches should be explored to obtain decision-relevant information (e.g. Wilby and Dessai, 2010; Maraun et al., 2017).

Such **complementary 'bottom-up' approaches** focus on a better understanding of sensitivity and vulnerability to past and present climate variability, typically in the wake of an extreme event, in order to develop relevant adaption strategies (Wilby and Dessai, 2010). Methods, which all have not yet been widely applied in Switzerland, may include storyline simulations, synthetic stress test experiments, and scenario-neutral response surfaces. Examples of scenario-neutral approaches that assess the sensitivity of hydrological responses to a plausible range of climate changes (instead of the outcome of individual scenarios) were presented e.g. by Prudhomme et al. (2010), Sauquet and Prudhomme (2015), and Vormoor et al. (2017). The development of synthetic stress test modelling experiments has been tested to explore the intrinsic drought sensitivity for a range of different catchments in Switzerland (Staudinger and Seibert, 2014, Staudinger et al. 2015, 2018, Stoelzle et al., 2018) and is treated more detailled in Section 6 of this report. Outcomes of alternative approaches based on qualitatively derived climate input are considered especially beneficial to prioritise adaptation measures for areas most sensitive to deviations from the present-day climate. Their application reduces computational costs and enables better informed individual model simulations to bridge the gap between climate research and stakeholder needs by involving stakeholders in the development of relevant scenarios and qualitative storylines (Rinaudo et al., 2013; Sauquet and Prudhomme, 2015; Maraun et al., 2017).

Take-home messages

- Previous hydrological impact studies for Swiss catchments agree on mean changes: winter low flows will increase, summer low flows will decrease. Commonly, a higher risk of extreme summer low flow events and increased water stress is expected as a result of a general decrease of summer flow, warming, and assumed increased water demands.
- Modelling efforts with a targeted exploration of projected low flow extremes have been limited, i.e. hindered by known limitations of model chains to assess extremes in general and of the delta-change method based CH2011 scenarios in particular. As a result, studies did not focus on event-scale changes of extreme low flow and drought.
- For the assessment of low flows specific uncertainty sources in climate change impact model chains relate to: i) limitations of GCM–RCMs ensembles regarding the representation of (dry) extremes, ii) limitations of chosen empirical-statistical downscaling methods regarding the representation of extremes, iii) internal climate variability, and iiii) limitations of chosen hydrological models and calibration strategies to represent low flow conditions and processes adequately. Comprehensive studies characterising these different uncertainty sources specifically for low flow projections are lacking (for Switzerland) and should be encouraged.
- Improvements have been made continuously but especially regarding extremes large uncertainty remains, part of which is irreducible due to internal climate variability and causes are hard to disentangle. The confidence in hydrological projections regarding changes in low flow events should be increased by excluding inappropriate methods and models from the ensemble depending on the specific objectives. Furthermore, scientists call for a shift to more complementary efforts into bottom-up vulnerability approaches, incl. stress-test scenarios or storyline simulations.

5 Role of seasonal alpine snowpack, glaciers, and hydrological regime shifts in the context of climate change impacts on low flow events

Keywords: elevation, glacier, recharge, regime, region, sensitivity, snow, warming, time shifts

Changes in glaciers, snow regimes, and alpine hydrological regimes are among the most distinctly observed consequences of warming and represent key drivers in the hydrology of Switzerland. Consequently, this section elaborates specifically on the knowledge of the particular role of nival and glacial components for periods of low streamflow from studies covering Switzerland and other alpine regions.

Changes of snow cover and snowmelt runoff are a major concern in the context of the hydrological response to climatic change in mountain regions worldwide (Barnett et al., 2005; Stewart, 2009, see also Hydro-CH2018 contribution on 'Snow and glaciers'). According to the IPCC AR5 assessment there is "very high confidence that the extent of Northern Hemisphere spring snow cover has decreased since the mid-20th century" (IPCC, 2014). In large parts of Switzerland, snow represents the dominant control on annual streamflow and groundwater regime patterns (Spreafico and Weingartner, 2005; Schürch and Kozel, 2010). Systematic increases of the ratio of liquid to solid precipitation and resulting changes of the snow cover lead to distinct changes in recharge timing and consequently also influence temporal drainage from soil and groundwater to the streams as baseflow. Generally, in the absence of changes in net precipitation, a decreasing snow component results in shifts of the streamflow regime towards increases in mean flows in the cold season at the expense of decreases in mean flow in the warm season. Earlier snowmelt may lead to an earlier depletion of recharged water in spring/summer and hence altered streamflow recession during dry weather periods. As the trend analyses and modelling studies reviewed in the previous sections suggest, such changes can also have important implications for the low flow season. Snow anomalies, i.e. low snow water equivalents and early melt-out dates, contributed to the development of past low flow events in Switzerland, for instance, in 1947 (Schorer, 1992) and in 2011 (Zappa et al., 2012; Seneviratne et al., 2013).

Recently the role of earlier snowmelt and 'snow droughts' and their potential to propagate into summer low flows have been addressed in studies for the western parts of North America (Barnett et al., 2008; Luce and Holden, 2009; Jefferson, 2011; Huntington and Niswonger, 2010; Beaulieu et al. 2012; Safeeq et al., 2005; Godsey et al., 2014; Cooper et al., 2016, 2018; Mote et al., 2016; Painter et al., 2017; Woodhouse and Pederson, 2018), where correlations between monitored spring snow water equivalent and summer streamflow have traditionally been used in water management to forecast summer water supply. However, those regions are characterised by summer-dry climatic conditions. In the moderate humid climate of Switzerland where precipitation is more equally distributed throughout the year the influence of warm season precipitation on seasonal streamflow development is larger (Jenicek et al., 2016). Precipitation patterns in Switzerland thus hinder a clear attribution of changes in summer low flows to changes in winter snowpack.

In Swiss research the influence of the snowmelt contribution to runoff and its change is mostly discussed as a driver of within-year streamflow variability and **streamflow regimes**, e.g. by Hänggi and Weingartner (2011), Köplin et al. (2011, 2012, 2014), Rössler et al. (2014), and Speich et al. (2015). It has been shown that catchment elevation is an indicator of the regime and climate change response types in Switzerland. According to Köplin et al. (2011, 2012) the influence of the snow component is especially relevant for Swiss catchments with mean elevations in a range between about 1000 and 2500 m a.s.l., where temperature is the dominant driver of hydrological response. Hence, catchments in this elevation range are considered as being particular sensitive to warming and large relative changes of seasonal flow are expected. Such changes are relevant for many reasons, yet they cannot be directly translated to a large sensitivity with respect to low flow events. The low flow season of high-elevation catchments in Switzerland has been the winter period (for which continued increases are expected, see Section 4). Decreases in summer streamflow will not necessarily lead to the occurrence of extremely low flow levels. For this reason past studies addressing low flows (e.g., Meyer et al., 2011b) focused mainly on catchments in the Swiss Plateau region with regime minima in summer and autumn. Cases where the decreasing influence of the snow component could lead to a transition of catchments' regimes from snow-domination to rainfall-domination may be of particular interest. Such a transition may then result in a shift of the low flow season from winter to summer, as projected for the Rhine (Bernhard and Zappa, 2012; Bernhard et al., 2011; see also Section 4). However, relative flow deficiencies during the high flow season in currently nival and alpine streamflow regimes due to seasonal shifts and decreasing contributions of snowmelt may also be relevant for the development of low flow events during recession periods later in the year or further downstream.

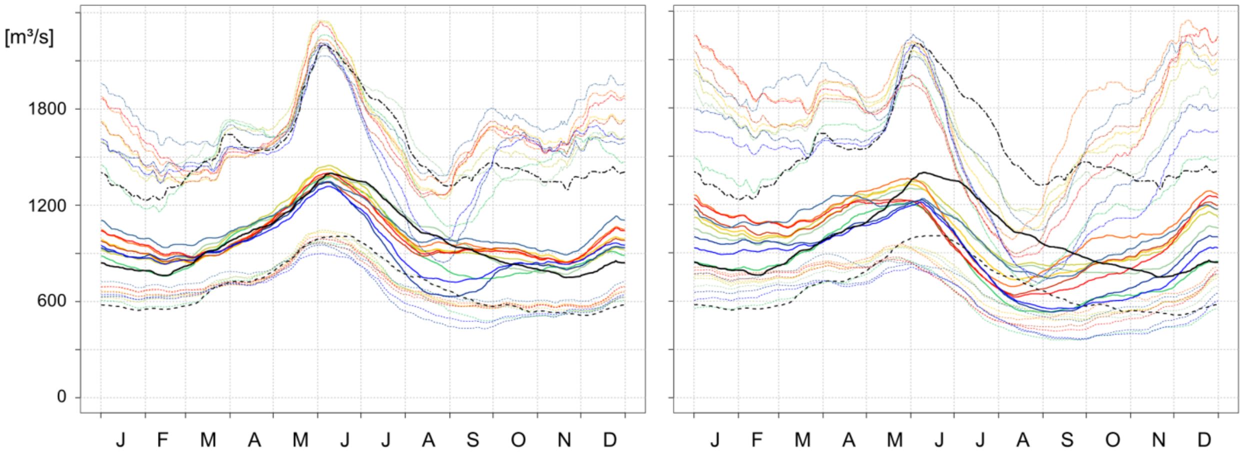


Figure 5-1: Projected discharge for the Rhine at Basel based on results from the CCHydro study by Bernhard and Zappa (2012) presented in FOEN (2012b): 10%, 50%, and 90% quantiles for the control period (black lines) and CH2011 climate scenarios (coloured lines), on the left for the near future period around 2035, on the right for the long-term future around 2085 (graph slightly modified).

Several studies have addressed the **link between snow and low flow events** for catchments in Switzerland. Often the focus in these studies was on relative summer low flows. Accounting for snow accumulation and melt processes in standardised meteorological drought indicators demonstrated a drought-mitigating flow augmentation from snowmelt in Swiss catchments (Staudinger et al., 2014). Efforts have been made to better incorporate snow in streamflow forecasting and early recognition of drought and critical water resources deficits (Zappa et al., 2012; Jörg-Hess, 2014; Jörg-Hess et al. 2014, 2015; Griessinger et al. 2016; Zappa et al., 2015). All these studies have shown that a better representation of snow resources can improve streamflow modelling. However, the largest positive effects have been found for modelling streamflow in spring (Jörg-Hess et al., 2015), i.e. during the high flow season, and in snow rich years (Griessinger et al., 2016), whereas in the context of extreme low flow events the typical low flow season later in the year and the snow poor years are of interest. Jenicek et al. (2016) analysed modelled seasonal snow characteristics and low flow indices for 14 alpine and prealpine catchments in Switzerland. They showed that snow and summer precipitation had a combined effect on summer low flows. Snow was a better predictor for the variability of summer low flows if only years with lower than average preceding precipitation were considered. However, for all catchments a considerable interannual variability was found that could not be explained even if both predictors, liquid precipitation and snow, were taken into account (Jenicek et al., 2016). Subsequent analyses of the output of future scenario modelling by Jenicek et al. (2018) suggest the largest decrease in the snowmelt runoff contribution to summer flow for catchments above 2000 m a.s.l.. However, summer for those alpine study catchments represents a high flow season rather than a low flow season. Therefore these projected changes may have implications for the water availability in summer and a preconditioning for potential low flow events, yet they do not necessarily lead to more severe low flow events. To explore the role of snow water resources for extreme events, an analysis that links seasonal snow characteristics not only to relative streamflow deficiencies but also to low flows in an absolute sense is imperative.

The cross-seasonal impact propagation from **snowmelt recharge processes into changed low flows** has also been subject of studies outside Switzerland. Barnhart et al. (2016) suggest that in the western US snowmelt rates broadly control hydrological partitioning between evapotranspiration and streamflow production due to the recharge mechanism being driven by the intensity of snowmelt. Their results call for more process-based analyses of changes in snowmelt rates and recharge to better understand catchments' streamflow response rather than the pure quantification of changes in the snow to rain phase of precipitation. Musselman et al. (2017a, b) demonstrated that a contraction of the snowmelt season may limit the potential for high snowmelt rates typical for spring and early summer and may lead to a reduction in the meltwater volume produced at high snowmelt rates. In addition, it has been shown that representing the high spatial variability of radiative forcing and snowmelt in mountainous terrain adequately is critically important for groundwater recharge quantity and timing (Tague and Grant, 2009; Hood and Hayashi, 2015). In temperate regions generally groundwater recharge is largest during spring and usually it is assumed that conditions towards the end of the snowmelt period are most effective at recharging groundwater. Although the intra-annual maxima of pluvio-nival and nivo-glacial groundwater regimes in Switzerland clearly follow the melt period (Spreafico and Weingartner, 2005; Schürch and Kozel, 2010), data and research on groundwater recharge at the scale of Switzerland are still limited. This research gap relates in particular to karstic and alpine areas (Björnsen Gurung and Stähli, 2014). Based on a snowmelt model calibration dataset obtained from the karstic Vers Chez le Brandt cave research catchment in Switzerland, taken as an oversized natural lysimeter, Meeks et al. (2017) found that three commonly used snowmelt models of varying complexity all underestimated total snowpack drainage, underestimated the rate of early and midwinter drainage, and overestimated spring snowmelt rates. The authors conclude that in low alpine settings the importance of the contribution of mid-winter melt to groundwater recharge is more similar to that of springtime snowmelt than the tested models would imply. Although the majority of groundwater recharge comes from snowmelt and the snow cover and seasonally frozen soil largely influence infiltration and recharge patterns in many regions, these processes are if at all only poorly treated in models (Lundberg et al., 2016). Given the crucial role of groundwater supply (baseflow) for streamflow during low flow events, hydrological research should pay more attention to groundwater resources and recharge processes and how climate change, in particular decreasing snowpacks along with potential increases in (liquid) winter precipitation, may impact them.

As explained in Section 2, **contributions from glacierised catchment parts** have partially compensated streamflow deficits in the past especially in the case of warm summer low flow events. Although ice melt contributions are minor in terms of long-term average fractions at the scale of large river basins, during late summer/autumn low flow events they can be in a relevant order of magnitude for sustaining streamflow. This has been shown for some past events in the Rhine basin (Stahl et al., 2016, 2017a, b, Figure 5-2); with fractions of up to about 20% during the 2003 summer event at the German Mittelrhein section. The climate change response of European glaciers and the expected timing of the maximum contribution to runoff ('peak glacier water') is a complex but extensively studied topic (e.g. Pellicciotti et al., 2010; Huss, 2011; Farinotti et al. 2012; Huss et al., 2013, 2017; Kobierska et al., 2013; Fatichi et al. 2014; Vincent et al., 2017; Hanzer et al., 2017; Huss and Hock, 2018; Schaefli et al., 2019). It is undisputed that with ongoing warming glacier melt contributions in summer will be lower than in the past or even disappear in some catchments. As shown by Stahl et al. (2017b), for low flows this change is not that relevant at the scale of alpine catchments but rather in the downstream reaches of the larger basins where the period of the ice melt flow component overlaps with the season typical for low flows.

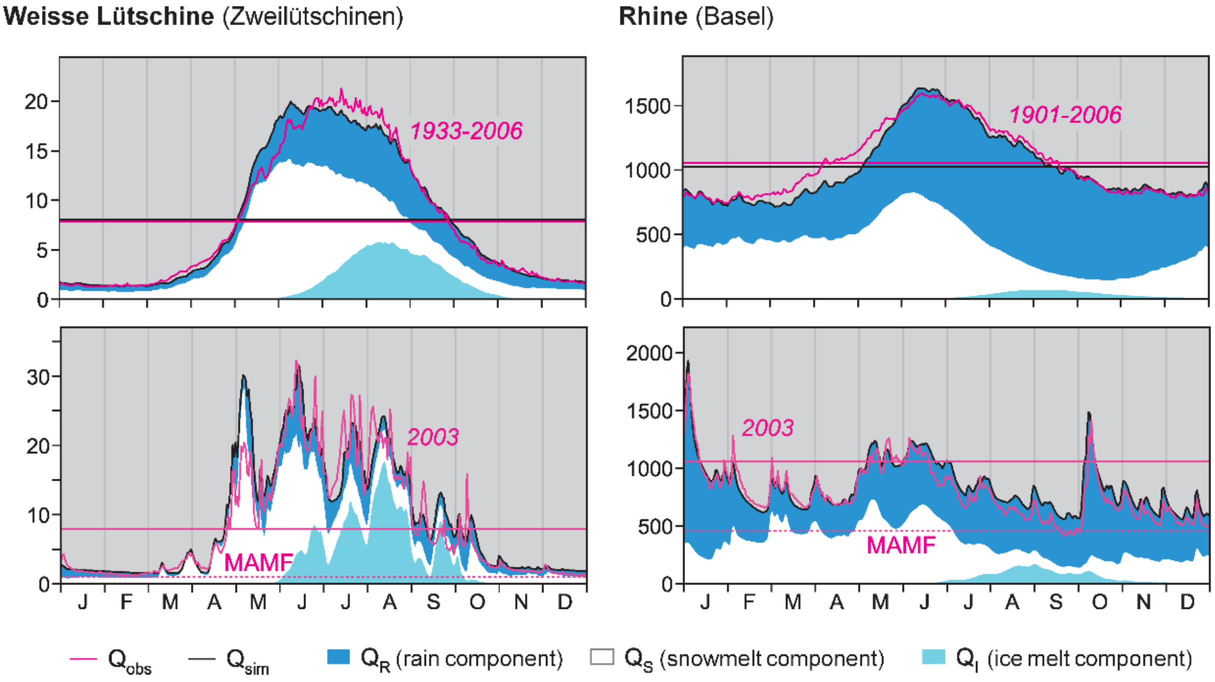


Figure 5-2: Observed and simulated streamflow [m³/s] with simulated components: long-term regime (upper panel), summer drought and heat year 2003 (lower panel) with long-term mean (solid lines) and mean annual minimum flow (MAMF dashed lines); modified from Stahl et al. (2016).

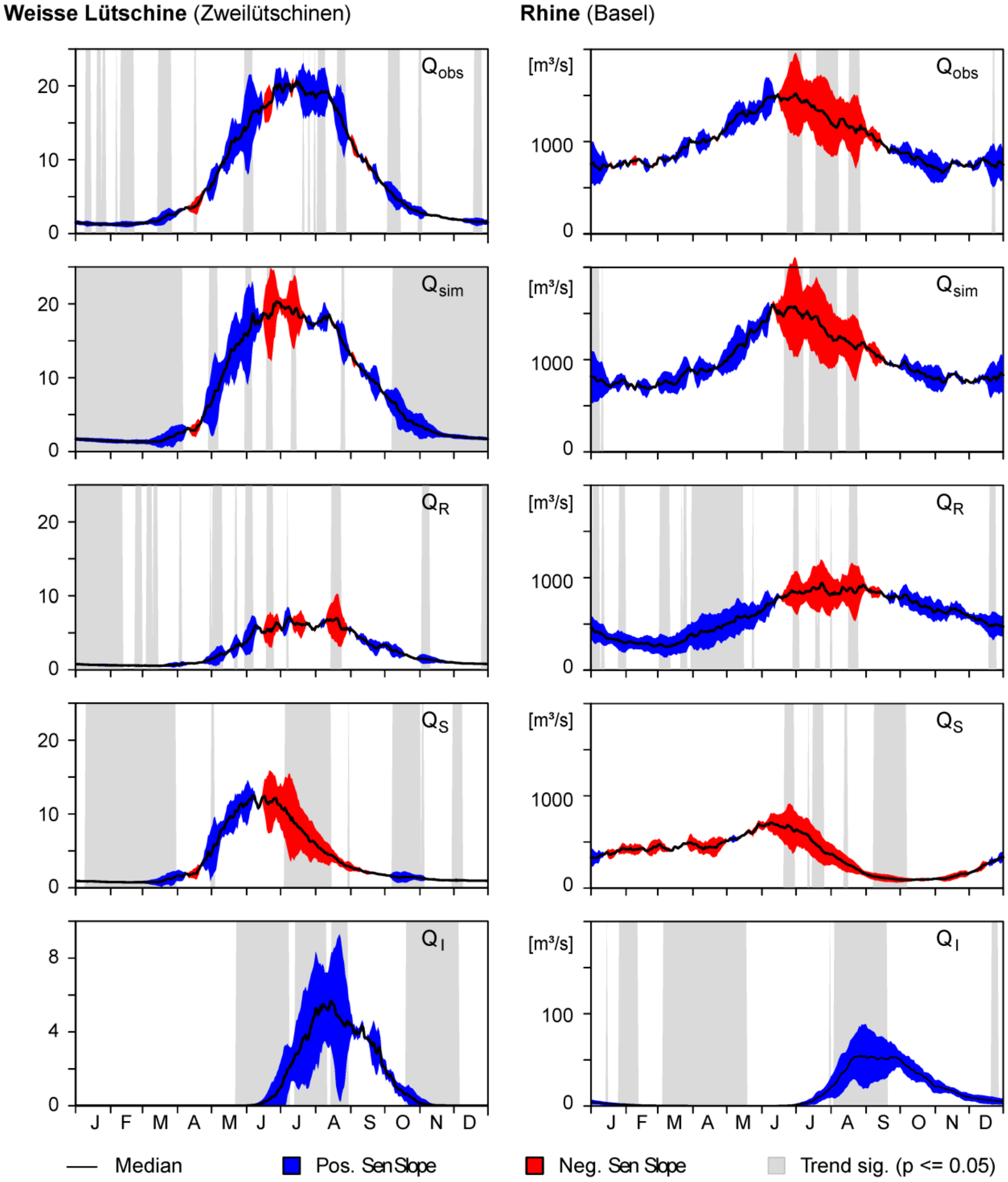


Figure 5-3: Regime changes of observed (Q_{obs}) and simulated total streamflow (Q_{sim}) and its modelled components resulting from liquid precipitation input (Q_R), from snowmelt input (Q_S), and from ice melt input (Q_I) over the period 1951–2006 according to data from Stahl et al. (2017b) for the alpine Weisse Lütschine catchment and the Rhine basin at Basel. Trend magnitudes calculated as Sen Slope for each day of the year (based on moving averages over seven days) and significance according to Mann-Kendall test. Note the differing y-axis scaling for the Q_I component (bottom panel)!

Modelling to quantify the relation of glacier ice melt, snowmelt, and rain components of streamflow requires the tracking of all runoff generated from the different processes (Weiler et al., 2018). Such a tracking then needs to account for the mixing of melt components in soil water, groundwater, lakes, rivers etc. and many assumptions on catchment storage are necessary. Assuming limited mixing to track the effects of the three contributions to streamflow along the river Rhine in the ASG project's model chain allowed to investigate time trends in the individual streamflow components (Figure 5-3). In the glacierised headwater catchment, the Weisse Lütschine, as well as in the river Rhine downstream at Basel negative trends in the summer months originate from reductions in the rain component and in the post-peak snowmelt component of streamflow. For the majority of the studied headwaters, these reductions were partially compensated by increased glacier melt over the period 1951–2006. However, the example of the Weisse Lütschine also shows that care must be taken when interpreting trends calculated from modelled streamflow: the highly detailed seasonal trend magnitudes in July and August differ from those derived from observed streamflow. As described in Section 4 even though performance measures may suggest overall good representation of streamflow, specific characteristics such as trends in a particular time of the year or low flows may be more uncertain.

To summarise this section, seasonal shifts as well as continued and expected decreases of the nival and glacial streamflow components are factors that may contribute to a higher future risk of severe low flows and should be considered within the complex development of low flow events (see Figure 2-1). Yet, based on these aspects alone, no conclusions can be drawn on changes of extreme low flow events. A clear attribution of summer low flow variability to the combined changes in winter snowpacks, rates of recharge from snowmelt, reduced glacier melt, where applicable, and direct summer climate is still lacking.

Take-home messages

- Many studies expect regime-shifts with an earlier snowmelt and a resulting earlier intra-annual depletion of stored water to contribute to an overall decrease of summer/autumn flow levels. In addition to the expected higher interannual climate variability and enhanced evapotranspiration losses, this may lead to an increased risk of extreme summer/autumn low flow events.
- The cross-seasonal link of winter snowpack and spring snowmelt to summer low flow is an emerging topic but results vary and assessment of potential requires more work. Contrary to summer-dry climates in other mountain regions, an influence of long-term changes in snow characteristics on the developments of summer low flows is difficult to detect in Switzerland due to its wet summer climate. In addition, a better understanding, how changed snowmelt dynamics may affect groundwater recharge processes apart from shifted timing is needed.
- In the past, glacier melt had a certain mitigating role in summer/autumn low flow events downstream. In general, the future evolution of glaciers and the peak water time appear relatively clear and well-studied for Swiss glaciers, but conclusions on effects on streamflow and future low flow events require scale and case-specific assessments in combination with the changes in snow and rain components of streamflow.

6 Sensitivities of streamflow to changes— role of catchment storage characteristics and human interventions

Keywords: aquifer, baseflow, drainage, human, hydropower, memory, recession, recharge, recovery, release, response, scenarios, streamflow–groundwater interactions, storage, stress test, subsurface, regulation, reservoir, water use

Climate determines hydroclimatic regimes with seasonal water balance surpluses and deficits, and may largely drive recharge, but the propagation of the resulting signals, streamflow recession, baseflow, or low flow recovery, are also strongly dependent on inherent system characteristics (e.g. Stoelzle et al., 2014; Bloomfield et al., 2015; Van Loon, 2015). Consequently, catchment hydrology may respond differently to a meteorological drought event. Figure 6-1 illustrates such differences in streamflow for four past events in Swiss catchments that are not strongly influenced by snow storage. The number of days below Q_{95} as a low flow indicator shows some differences among the catchments even though climate variable anomalies in affected calendar months were rather similar. Such precipitation–temperature-plots are helpful to identify the strength of climatic drivers related to low flow magnitude.

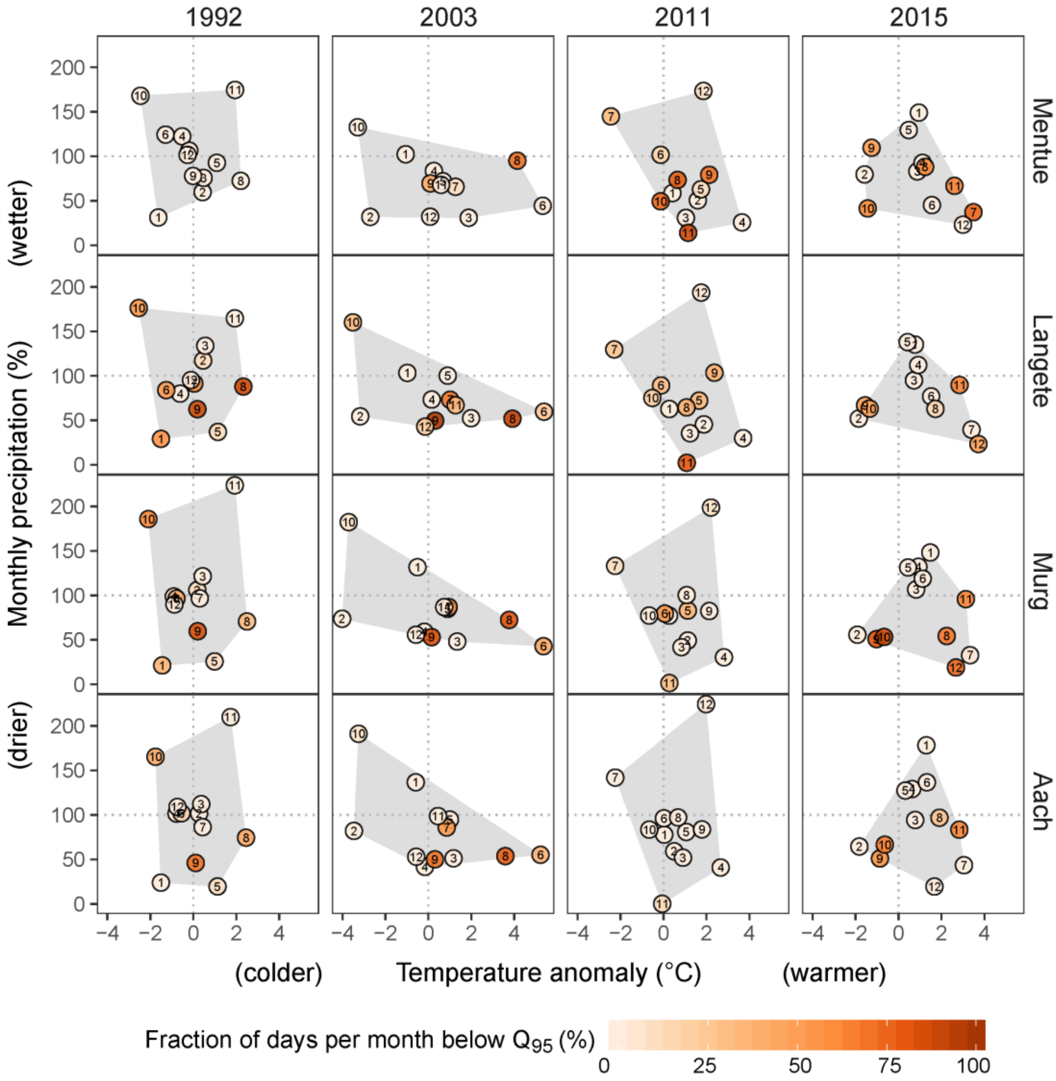


Figure 6-1: Deviations of temperature and precipitation from mean (dashed grid) in the period 1986–2015 and fraction of days with streamflow below Q_{95} (Q_{347}) for each month (circles with 1: Jan,.., 12: Dec) in selected past low flow years for four catchments in the Swiss Plateau.

This section deals primarily with **non-climatic controls** that may cause such differences in low streamflow behaviour, in particular natural catchment storage characteristics. Yet there are also impacts of water resources management measures. Both aspects may be critical to Swiss catchments' low flow sensitivity to changed hydroclimatic conditions. The role of human alterations and river regulation are briefly addressed in 6.1 to provide insight into potential drivers of changes, but most research efforts have focused on natural systems. From a methodological point of view, two different approaches dominate the literature on this topic. Empirical-statistical studies are based on streamflow records and have focused on the comparative characterisation of statistical properties such as recession behaviour and baseflow; these are summarised in 6.2. Process studies of particular catchments, rivers, or river reaches have aimed for better system and process understanding and description either based on data from well-instrumented field sites or by the use of (complex) hydrological and hydrogeological models; these are summarised in 6.3. Then, Section 6.4 explores initial efforts to bring all influences together towards a holistic characterisation of low flow sensitivity.

6.1 Human interventions

A considerable part of the flow of Swiss streams and rivers is affected by water management infrastructure and **human water use activities** (Margot et al., 1992; Baumgartner et al., 2007; Wehren et al., 2010; EAWAG, 2011; see also Hydro-CH2018 synthesis report "Impacts on water management"). The magnitude and seasonality of observed low flows can be altered by such water management operations (e.g. Pfister et al., 2006, Pfaundler and Wüthrich 2006). Low flows (or even no flows) may even be caused entirely artificially by regulation through damming and release of only the required minimum flow (*Restwasser*) or may be temporally and very quickly caused as part of hydropeaking schemes (*Sunk*). The national research programme NRP 61 "Sustainable water management" concluded that in Switzerland, particularly in non-alpine regions, the influence of socio-economic development and increasing water demands on water resources are more relevant than the expected impact of climate change at least until the mid of the 21st century (Weingartner et al., 2014; Björnsen Gurung and Stähli, 2014; Lanz et al., 2014; NFP 61, 2015a, b).

Relevant to low flows, Van Loon et al. (2016a, b) describe the propagation of a drought signal in the Anthropocene (Figure 6-2). Soil moisture and hydrological drought follow unusually low inputs to the hydrological system, such as a lack of rain, snow/glacier melt but also irrigation or sewage return flows, and unusually high outputs, such as enhanced evapotranspiration but also increased water abstractions. Low flow characteristics may further be affected by limited storage in soil, groundwater, lakes and also generally by regulation of reservoirs. Human activities may consequently modify the propagation of drought through changed water input, output, and storage. Data on these influences are rare. While maps of major diversions and reservoir storage (from hydropower operations mainly), including the locations of residual flow stretches ('Restwasserstrecken') are available in the Hydrological Atlas of Switzerland, quantitative assessments in particular for low flows are largely lacking.

While research has focussed mainly on near-natural systems, within the framework of the current research initiative of the International Association of Hydrological Sciences "Panta Rhei" recently scientists claimed that, to develop strategies for a sustainable future management of water resources including low flow situations, more inter-disciplinary research of real-world coupled human water systems by explicitly including the multi-directional relationship between natural processes and human activities is needed (Montanari et al., 2013; Sivapalan et al., 2014; Savenije et al., 2014; Sivapalan, 2015; Van Loon et al., 2016a, b). Ideally such research initiatives need to be case-specific, should not rely exclusively on quantitative modelling tools but involve scientists with natural and social perspective as well as local stakeholders, and may explore the potential of qualitative scenarios. Case studies in such a socio-hydrological context have been presented for regions in Western Switzerland by Weingartner et al. (2014) and Milano et al. (2015a). Both studies, however, were based mainly on mean monthly water availability, i.e. did not specifically address extreme low flow events, and both identified the lack of data on water use and transparency as a key obstacle.

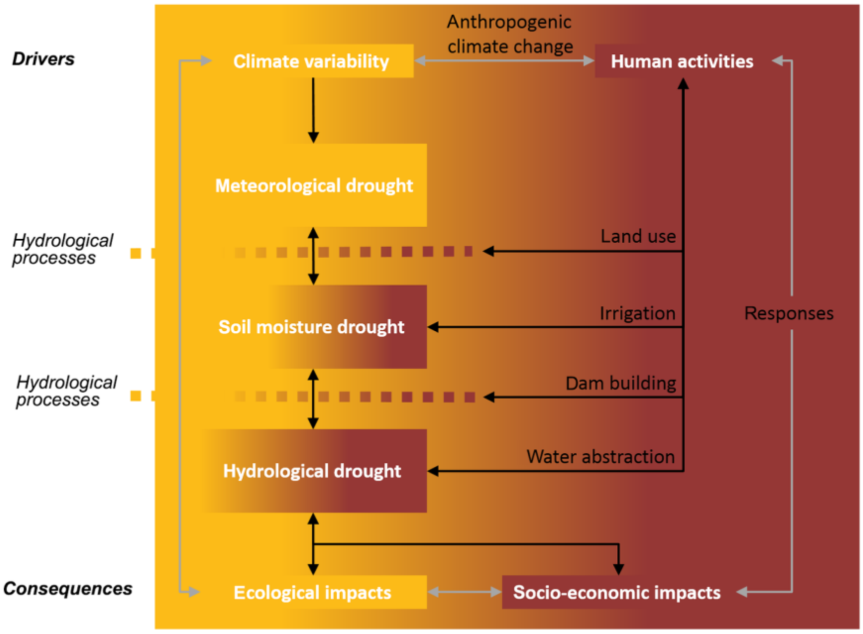


Figure 6-2: Drought propagation in the Anthropocene. Graph from Van Loon et al. (2016b) modified from Van Loon et al. (2016a).

During extreme summer low flow events widespread problems are related to water withdrawals from surface waters for **agricultural irrigation** that conflict with ecosystem flow protection objectives. Issues occurred and were documented in the drought and heat summer of the year 2003 (BUWAL et al., 2004; FOEN, 2012; Siegrist, 2015). Approximately one fourth of agriculturally used land in Switzerland has a potential demand for irrigation; in the summer of 2003 net irrigation requirements reached the limits of river water availability (Fuhrer and Jasper, 2009; Fuhrer and Jasper, 2012). During severe low flow situations **sewage plant effluents** potentially aggravate water quality issues but also make a quantitative contribution to streamflow (e.g. Hunkeler et al., 2014; KLIWA, 2018), thus playing an ambivalent role. Model runs incorporating and neglecting **reservoir operations** as well as analysis of historical streamflow allowed to estimate the average effect of reservoirs as increasing streamflow of the Alpine Rhine in winter by about +30% and reducing streamflow in summer by about -10% compared to natural conditions (Krahe et al., 2011). The role of reservoir storage capacity and hydropower operation for observed changes of low flow indices has been discussed in several studies at the Rhine basin scale (Pfister et al., 2006; Krahe et al., 2016; Weingartner, 2017; ICPR, 2018; see also Section 3 of this report) but detailed investigations of the effect of reservoir operation on low flows have been limited.

In response to the “Postulat Walter” the Swiss Federal Council and the FOEN provided a report (FOEN, 2012) and commissioned three follow-up reports (Chaix et al., 2016; Dübendorfer et al., 2016; Wehse et al., 2017) as support and practical guidance documents for the cantons to identify regions and sectors with need of action and to develop **regional management strategies** to tackle potential general water shortage as well as temporary exceptional water shortage episodes and water use conflicts during low flow events in the future. Following the recommended procedure, some cantons have already accomplished a situation analysis or even implemented water resources management strategies (Zahner, 2017). In particular the realisation of **multi-functional reservoirs**, either by the reorganisation of the management of existing dams after the forthcoming expiration of their concession agreements from 2035 onwards or by exploring the potential for the construction of new dams, has been proposed as a key measure to cope with future water shortage situations expected for certain regions (Weingartner et al., 2014; Lanz et al., 2014; Thut et al., 2015, 2016). This is further explored in an ongoing research project “Wasserspeicher” within Hydro-CH2018 (Brunner et al., 2018; Hydro-CH2018 Wasserspeicher, 2017).

6.2 Empirical analysis of low flow behaviour with catchment characteristics

The analysis of **recession curves and baseflow indices** derived from hydrographs has been widely used to study and compare the characteristic behaviour of catchments during low flow (Tallaksen, 1995; Smakhtin, 2001). The aim of most of these studies was to find catchment characteristics that explain the variability of low flow events in space and time and allow predicting low flow characteristics of ungauged catchments, which may then also inform climate sensitivity. Pereira and Keller (1982a, b) found positive correlations of the baseflow component with a permeability index and drainage density, indicating the influence of hydrogeological properties, but overall the multiple regressions with a sample of eleven Swiss basins were not significant. Investigations at several gauging stations in the Emme catchment revealed that the shape of the recession curve can vary over short distances and appears to depend on local conditions in addition to catchments scale characteristics (Käser and Hunkeler, 2016). Overall, however, the comparability of recession characteristics derived with different methods is limited (Stoelzle et al., 2013; Thomas et al., 2015).

Broadly, **baseflow** is defined as the proportion of flow that originates from groundwater and other stored or delayed sources (e.g. Hall, 1968; Tallaksen, 1995; Smakhtin, 2001; Gustard and Demuth, 2008). Standard methods for separating hydrographs into baseflow and quickflow (also termed direct flow or storm flow) were developed in humid, lowland catchments, where groundwater is the dominant control of baseflow, and quickflow components are assumed to disappear a few days after the last rain event. In such environments it may be reasonable to equate the separated baseflow with groundwater outflow as it is often done in hydrological literature. In alpine catchments terming this proportion of streamflow ‘slowflow component’ might be better, since it often represents a combination of multiple delayed contributions to streamflow. Comparing tracer-based analyses with classical graphical hydrograph separation, studies found that the latter leads to larger baseflow estimates the larger the influence of snow in the catchment (Kronholm and Capel, 2015; Miller et al. 2016). If the multiple components of streamflow during recession can be better distinguished, it will also be easier to estimate potential changes in the future under changed hydrological conditions. In Switzerland the analysis of baseflow indices for the summer period from May to October for 59 catchments by Meyer et al. (2011a) showed that the calculated summer baseflow indices for alpine catchments are clearly influenced by snow and glacier melt, that the lowest baseflow indices occur in catchments along the northern rim of the Alps and in the eastern part of the Swiss Plateau region (regime types pluvial supérieur and nivo-pluvial préalpine), and that baseflow indices vary among catchments across the Swiss Plateau region. A stringent consistency in the relation of baseflow with streamflow regime types or low flow regions was not found but some positive correlation with catchment area coverage by productive aquifers based on the hydrogeological map for Switzerland. In addition, Meyer et al. (2011a) suggest that the range of baseflow indices across the Swiss Plateau region might be linked to the variability of local hydrogeological conditions, and the relatively large baseflow indices found for catchments in the Jura regions might be explained by the influence of the important karstic aquifers of the Jura mountain range. Stoelzle et al. (2015a) suggest that a more detailed differentiation of multiple slowflow components would be more instructive for the identification of controls of low flows.

Eventually, sustained streamflow during recession and baseflow periods is a convoluted effect of drainage of a catchment's storages**. Storage** is the key function of a catchment, described to serve as buffer or filter for meteorological variability and extremes, and has increasingly received attention in research in recent years (e.g. McNamara et al., 2011; Buttle, 2016, 2018). It is important to note that different perceptual concepts of storage are used in hydrological literature and a clearer terminology is needed. Staudinger et al. (2017) discuss the issue and compared estimates of dynamic storage, i.e. the storage that controls streamflow dynamics, with other storage definitions. They found considerable relative fractions of slow draining groundwater storage even in high elevation catchments (Figure 6-3), where seasonally stored snow dominates absolute storage and annual turnover. Staudinger et al. (2017) conclude that even with less snow in the future and changed recharged mechanisms there may still be considerable capacity to sustain streamflow from stored groundwater during dry weather periods.

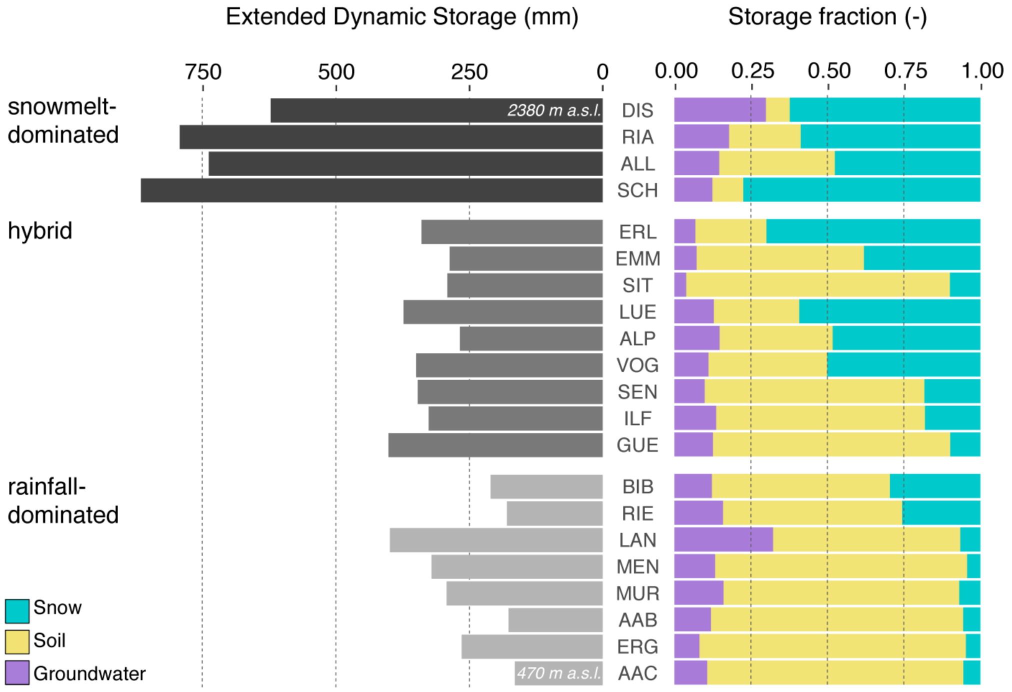


Figure 6-3: Estimates of the extended dynamic storage (left) with fractions of snow, soil, and groundwater storage (right) derived from hydrological modelling with the bucket-type HBV model for 21 Swiss catchments (ordered by mean catchment elevation). Data from the study by Staudinger et al. (2017); see original publication for full names of the catchments and explanation of extended dynamic storage.

There is wide consensus that in many Swiss catchments the snowpack and sometimes large natural or regulated surface water bodies act as important seasonal storages. In addition, studies on intrinsic catchment characteristics focused on **subsurface storage and hence on aquifers and hydrogeological properties**. However, for entire catchment and aquifer systems the assessment of quantitative hydrogeological properties of the bedrock is usually related to high uncertainties. Especially the deposits of the **Molasse,** as the bedrock unit of the Swiss Plateau region, are characterised by complex and spatially heterogeneous conditions which influence the low flow behaviour strongly (Naef and Margreth, 2017). Staudinger et al. (2018) have suggested a first approach to appraise bedrock aquifer characteristics across the Swiss Plateau for sensitivity studies at the catchment scale based on lithological maps and previous studies.

The catchments with the largest ratio of Q_{95}/Q_{50} in the Swiss Plateau region analysed by Staudinger et al. (2018) were those with the largest coverage of porous marine **sandstones** (**Obere Meeresmolasse formation**). Those catchments, the Langete and Murg catchments, are also characterised by particularly low interannual variability of baseflow indices (Meyer et al. 2011a). Other catchments dominated by the marine sandstones of the Molasse (e.g. Ürke, Chise) were found to be associated with remarkably high Q_{95} (Q_{347}) flow rates. The slowly and steadily draining sandstones appear to serve as an efficient storage (Margreth et al., 2013; Naef et al., 2015, Naef and Margreth, 2017). Naef and Margreth (2017) present findings from extensive field campaigns in 13 catchments across the Swiss Plateau regions characterised by different lithologies, in which they measured streamflow during low flow periods in the years 2015 and 2016 in a high spatial resolution. They found clear links between characteristic bedrock units and low flow behaviour for the sampled (sub)catchments, while it is still hard to generalise due to the complex, heterogeneous geological conditions found within the catchments without a uniform or clearly dominating lithological unit. Furthermore, exceptions to the expected low flow behaviour were often related to losing stream sections or the influence of human water withdrawals (Naef and Margreth, 2017).

Fischer et al. (2015) investigated sources of baseflow based on hydrochemistry and isotope sampling in a headwater of the Alptal catchment, a wet steep catchment with different **Flysch** lithologies and characterised by flashy streamflow and groundwater response to rainfall and rather steep recession curves. Their results indicate that deep groundwater, defined here based on the hydrochemical signature of springs, remained permanently connected to the stream network and dominated baseflow, whereas the numerous upstream wetlands, against expectation, appeared to have a rather passive role with minor contributions to baseflow. These findings may indicate a relatively low sensitivity to climate variability as long as groundwater storages are regularly and reliably recharged.

The hydrogeological storage capacity in various **alpine geological settings** and the response of alpine aquifers to climate change are largely unknown, i.e. to what extent recharge might be even more negatively affected by warming than expected (see Section 5) or the degree to which subsurface storage might offset the loss of seasonal snowpack storage (Markovich et al., 2016). Several recent studies highlighted the considerable subsurface storage capacity and relatively low young water fractions found in steep, high-elevation catchments (Sayama et al., 2011; Jasechko et al., 2016; von Freyberg et al., 2018; Floriancic et al., 2018; Staudinger and Seibert, 2014; Staudinger et al. 2017). As borehole data in these regions are lacking and studies have focused on describing the rapid runoff dynamics, the role of groundwater and the complementary dynamics of unsaturated and saturated zone have been rarely addressed in hydrological research for a long time. Field studies in alpine catchments world-wide call for a deeper exploration of the role of storage in bedrock, moraine, and talus deposits, the retreat of permafrost and rock glaciers, and their interaction in sustaining baseflow (e.g. Clow et al., 2003; Hood and Hayashi, 2015; Kobierska et al., 2015; Wagner et al., 2015; Rogger et al., 2017; Pauritsch et al., 2017; Harrington et al., 2018; Floriancic et al., 2018). Streamflow measurement campaigns during a winter low flow period in five alpine catchments in Switzerland demonstrated spatially highly variable flow contributions with a high relevance of subsurface outflow, localised groundwater inflow into streams, and losing stream sections (Naef and Margreth, 2017).

6.3 Process studies and modelling experiments for assessments of (future) low flow sensitivities

The project GW-Trend within the Swiss NRP61 programme showed that the complex groundwater–surface water interaction during low flow periods can differ among systems and suggested a number of relevant factors to be considered in Switzerland (Hunkeler et al., 2014). The study by Käser and Hunkeler (2016) in the upper part of the prealpine Emme catchment investigated whether **mountainous alluvial aquifers** can significantly contribute to total catchment outflow through storage depletion, and thus buffer low flows, or act mainly as a transit route for water stored elsewhere. Their results show that water releases from alluvial aquifers of limited extent and seemingly minor tributary systems can be substantial. In this case **subsurface outflow** from the alluvial aquifer during the final phase of the drought in November 2011 amounted to 85% of total catchment outflow. Hence, Käser and Hunkeler (2016) argue that the capacity of a catchment to yield water might be strongly underestimated if during such low flow situations only surface outflow is taken into account. Further, they found that the small and steep Röthenbach headwater catchment underwent the largest specific depletion in groundwater storage resulting in disproportionally large contributions to the total water turnover of the Emme catchment. Numerical groundwater simulations confirmed that such small, steep headwater catchments can supply nearly constant, relatively high amounts of groundwater outflow over several months without recharge, and, thus, can be an important component in sustaining the alluvial aquifer and streamflow conditions in downstream sections during drought periods (Hunkeler et al., 2014).

Käser and Hunkeler (2016) suggest that the longitudinal conceptualisation of baseflow generation (upstream–downstream links or lateral hydrological connectivity along the valley axis) and the analysis of coupled gauging stations, i.e. **nested catchment studies**, should receive more attention. According to Ameli et al. (2018) the quantification of groundwater outflow contribution from a headwater to downstream areas, also termed **headwater groundwater subsidy or mountain block recharge**, is one of the key issues in recent hydrogeological research. In their case study for the Maimai catchment in New Zealand they estimated that about 50% of recharge in a headwater catchment discharged outside of the headwater catchment divide and subsidised the main valley drainage network downstream.

Modelling has helped to gain insight into **groundwater–streamflow interactions** in the course of drought and low flow events. Most hydrological models have a limited representation of vertical processes, spatial variability, and do not explicitly incorporate groundwater–surface water interaction. Reasons are the high computational efforts and constraints in available information to parametrise the subsurface domain adequately (Käser and Hunkeler, 2016; Staudinger et al., 2018). Models of varying complexity were compared by Moeck et al. (2016) to investigate the influence of climate change on recharge related to subsoil parame-

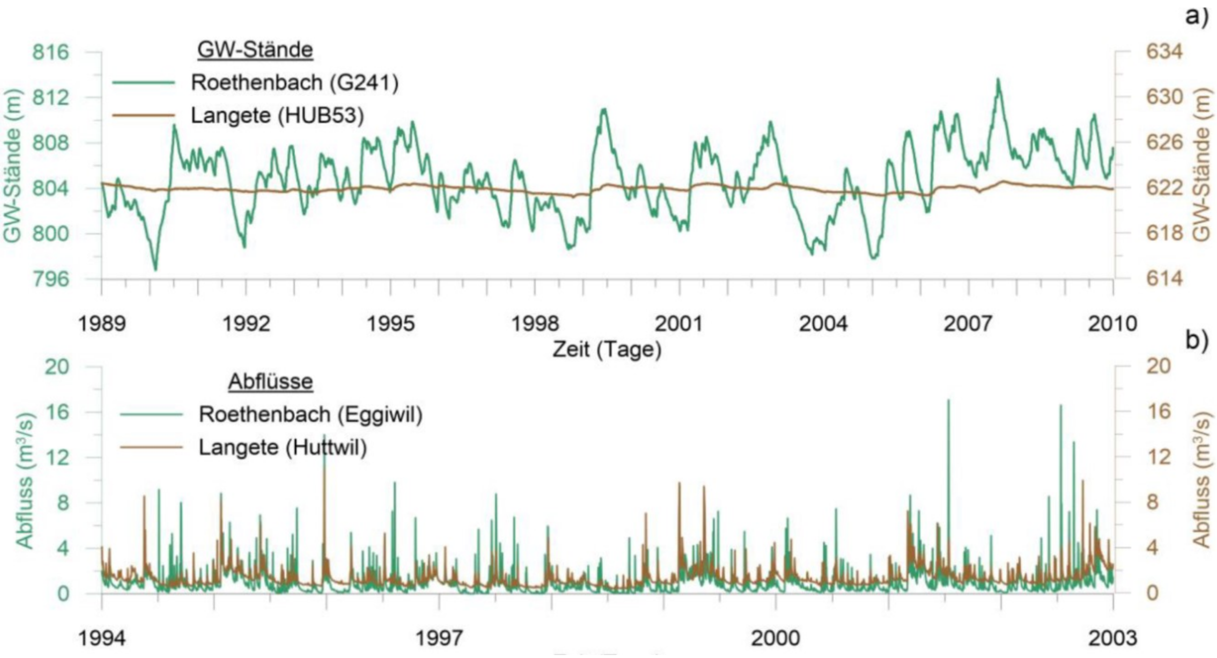


Figure 6-4: Observed groundwater levels (upper graph) and streamflow hydrographs (lower graph) in the catchments Langete and Röthenbach, both in the Swiss Plateau region (from Staudinger et al., 2018).

terisation and observation data employed during calibration. The models, although performing similarly in the reference runs, led to different recharge rates in climate scenarios, espe-cially under extreme conditions. Moeck et al. (2016) suggest that ensembles of climate projections should be applied to ensembles of hydrogeological models and calibration data should cover climatic extreme conditions. In a follow-up study, using a long-term recharge record from the Rietholzbach lysimeter site in north-eastern Switzerland, Moeck et al. (2018) found that the sensitivity to the calibration period was less pronounced in more physically-based models. The simplified models' failure to represent the most extreme recharge deficits volumes in the year 2003 may indicate that such models may be less suited to explore future changes. The inability of calibrated models to predict new extremes is an often-raised issue, which, however, has rarely been rigorously tested by experiments.

Particularly important for a climate impact assessment on low flows are groundwater–surface water interactions, including the role of direct and indirect recharge mechanisms (Allen et al., 2010). Application of the **integrated surface and subsurface hydrological model** HydroGeoSphere showed that a distinctly different low flow behaviour of the rivers Langete and Röthenbach (Figure 6-4) can be largely explained by a lower hydraulic conductivity of the bedrock in the Langete catchment resulting in a less responsive behaviour of streamflow and groundwater heads and by considerable subsurface outflow at the Röthenbach stream gauging station (Staudinger et al., 2018).

Simulations based on an integrated surface and groundwater model by Huntington and Niswonger (2010) suggest that in alpine catchments in California, dominated by low permeability bedrock and shallow groundwater flow paths, groundwater discharge to the stream is depleted in summer under climate warming scenarios not due to earlier groundwater recharge but because of earlier snowmelt recession that decreases stream depths, which with the **seasonal reversal of hydraulic gradients** initiates the shallow aquifers to drain to streams earlier, while drainage during the peak of snowmelt is limited due to the **bank storage** effect. By explicitly modelling variably saturated flow coupled with a land surface model, Markovich et al. (2016) studied the effects of progressive warming through perturbations of the baseline temperature signal with unchanged precipitation on two virtual hillslopes assumed to be representative for granitic and volcanic alpine systems in the Western US: a high diffusivity, low storage and a low diffusivity, high storage case. In hydrological literature such systems are typically also described as responsive to input and quickly draining systems vs. slowly draining systems with higher retention capacity and delayed response. With warming both hydrogeological settings exhibited a decrease in groundwater storage and runoff volumes, as a result of decreased recharge, thickening of the vadose zone, and increased evapotranspiration. Both were sensitive for unsaturated zone parameters, but the volcanic hillslope (larger storage capacity in both, its vadose and saturated zone, than the granitic one) was more sensitive. The consistent baseflow volumes of volcanic systems can be orders of magnitude larger than those of crystalline systems and buffered warming and earlier snowmelt in terms of streamflow volumes and timing, but at the cost of greater **reductions in groundwater storage** relative to the low storage granite hillslope. Markovich et al. (2016) conclude that baseflow-dominated, high storage systems in the Western US with its summer-dry climate may be more vulnerable in terms of late summer baseflow volumes than fractured, low permeability, and low storage systems, where baseflow after extended recession periods usually approaches zero, and so rather minor changes in mean and variance are to be expected with warming.

Similar findings and interpretations for catchments in that region had already been presented by Tague and Grant (2009) based on a conceptual model using ‘classical’ hydrological storage or recession coefficients to represent subsurface characteristics instead of explicitly modelling groundwater flow. Tague and Grant (2009) highlight that the influence of catchment recession characteristics (storage coefficient) is in a way counterintuitive, because a superficial analysis might suggest that a high storage, slowly draining system generally is more resilient to climate change, whereas in fact such systems are likely to continue to sustain baseflow, but may show the greatest absolute decreases in flow. The results from these studies outside of Switzerland, but in snow-dominated environments, suggest that in particular the reversals of groundwater drainage throughout the year due to snowmelt recharge and discharge together with bank and aquifer storage need to be better understood to appraise the climate change effect of warming, expected earlier and lower snowmelt peaks, and potentially changed drought event characteristics on low flows.

6.4 Towards comprehensive assessments of combined influences

The previous sections illustrate the complexity of catchment systems' internal storage and release dynamics of water that may consequently affect the responses to changed climatic conditions and the sensitivity in terms of low flows. Data and tools are therefore required that allow to test and disentangle climatic and non-climatic cause–effect relations. In addition, more and improved interdisciplinary research of groundwater and surface water hydrologists may be needed (Barthel, 2014; Staudinger et al. 2019). While for the use of more physically based groundwater models the parametrisation of the subsurface domain at large spatial scales poses a tremendous challenge, the formulation and parametrisation of the storage–outflow relationships for simpler hydrological models relies heavily on the availability and reliability of streamflow time series. Combined approaches and empirical analyses of hydrogeological characteristics and low flow behaviour of gauged catchments may provide **ways forward for the development of low flow specific parameter regionalisation**. Ideally such efforts will build on a widely distributed, long-term representative streamflow and groundwater monitoring network covering climatic and geological diversity but at scales sufficiently small to link catchment behaviour to specific hydrogeological units. Tague and Grant (2009) ask for a geoclimatic framework to guide the design of monitoring networks around the globe. Tague et al. (2013) presented an approach for transferring model recession parameters for ungauged catchments based on geological classification. According to Staudinger et al. (2018) **monitoring data needs** and recommendations to study the role of hydrogeological factors for the hydrologic response to climate change specifically in Switzerland include particularly:

i) the coordination of hydrometric and groundwater monitoring networks to support system analyses and inform modelling efforts,

ii) in terms of the streamflow monitoring network: better meta data to assess the degree of human influences (water use and abstractions), estimates of the subsurface outflow fraction for all operated streamflow gauges, and discharge data from gauges and springs monitored at the cantonal/community level, and

iii) in terms of information on hydrogeological characteristics: especially better information on hydrogeological characteristics (porosity and conductivity) of the various Molasse lithologies and more quantitative assessments of alluvial aquifer dimensions across Switzerland.

A survey by Naef and Margreth (2017) has provided an overview over additional streamflow gauges in Switzerland operated by cantonal authorities and assessed their potential suitability for low flow regionalisation analyses. Findings of the complementary comprehensive field investigations in this study, however, stressed the inevitable need of individual direct low flow measurements in ungauged catchments for validation.

Concepts are then needed to use models effectively to understand differences in response and sensitivities and ultimately to understand causes and effects. Even though it is debated whether simple conceptual hydrological models can be used to predict extremes outside their calibration conditions, given that low flow relevant storage characteristics are represented sufficiently, they can help to improve the **heuristic understanding of controls of baseflow and low flow sensitivity** particularly by intercomparison of catchments' behaviour under different **synthetic scenarios**, sometimes also termed **stress test scenarios** (Tague and Grant, 2009; Staudinger and Seibert, 2014; Stoelzle et al., 2014, 2015b; 2018; Staudinger et al., 2015, 2018; KLIWA, 2018). A typical question underlying such synthetic scenarios that aim to address catchment specific low flow sensitivity in modelling experiments is, for instance, **what** had happened in terms of low flows **if** a benchmark event, e.g. the 2003 drought event, had lasted longer or storage preconditioning had been more unfavourable.

Such modelling experiments were carried out as part of the FOEN funded groundwater–low flow project and Figure 6-5 shows exemplary results of a simple scenario. The test of lower preceding recharge conditions caused lower flows than actually experienced in the droughts of 1976 and 2003. The low flow events in these years could have been worse, had the preceding year been drier. Here the stress testing effect lasts longer in the Mentue and Langete catchments than in the Murg and Aach, which by August have recovered largely from the stress test. In the Mentue and Langete precipitation inputs over summer and autumn in 1976 and 2003 did not suffice and streamflow remained below the level originally simulated in these low flow years.

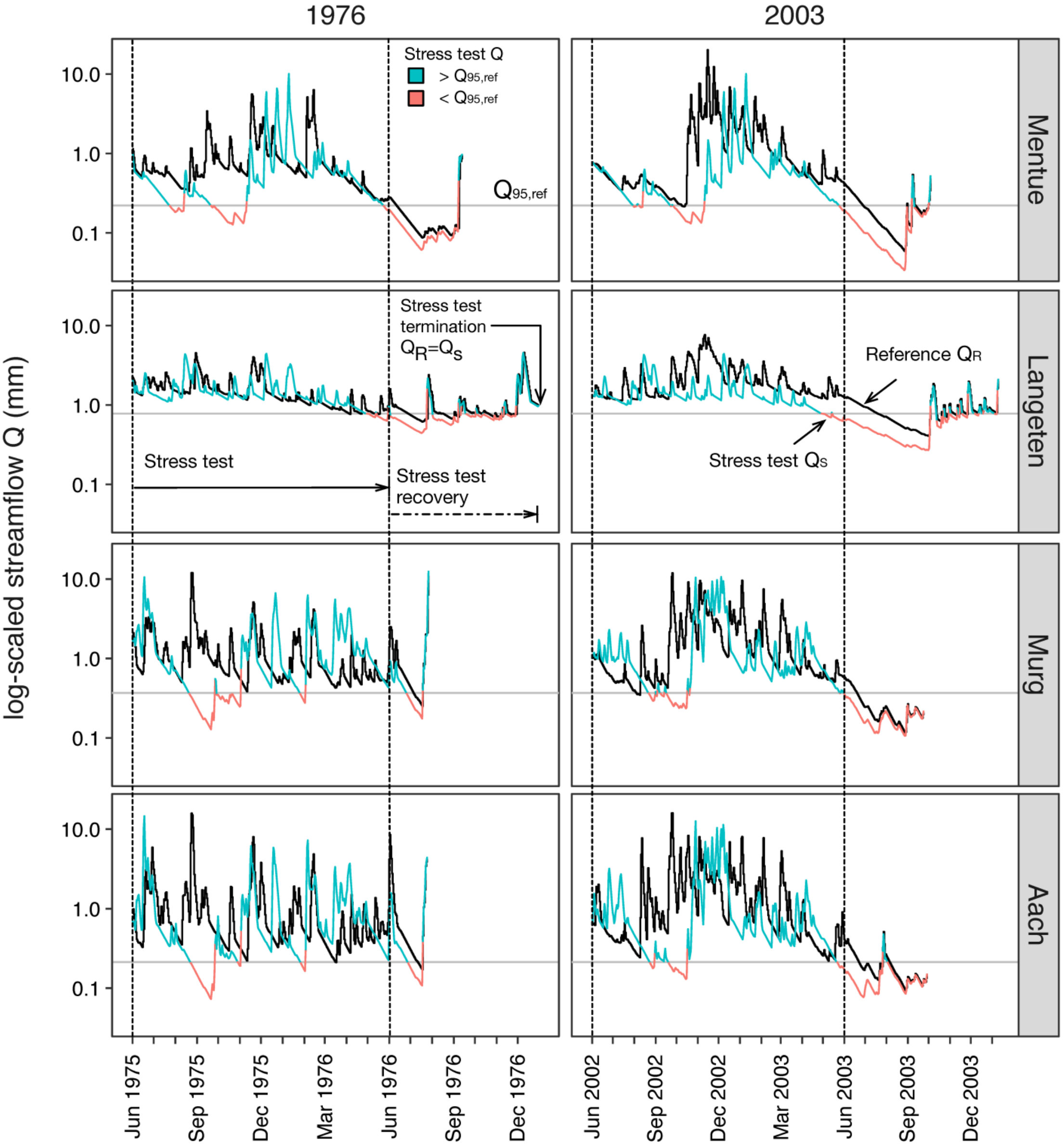


Figure 6-5: Example of a simple stress test for the same catchments in the Swiss Plateau region as in Figure 6-1, data from Staudinger et al. (2018): Streamflow is simulated for the period 1976–2015, the worst-case year (Jun–May) with minimum annual recharge is identified and corresponding climate data is used to replace the model input in the year preceding the drought. The system is taken as recovered from the stress test if reference (Q_R, black line) and scenario streamflow (Q_S, coloured line) have converged (≤2% difference).

Application of a set of recharge scenarios preceding droughts in eight mesoscale catchments in southwestern Germany with different dominant aquifer types indicated that the relationship between recharge and streamflow drought is more event-specific for karstic and fractured, and more catchment-specific, i.e. more consistent, for porous and complex aquifer types. In other words, the catchments can be divided into those with a shorter recharge memory, where streamflow drought is mainly climate controlled and those with a longer memory that are more catchment controlled (Stoelzle et al., 2014; KLIWA, 2018). The latter types of catchments with long memory and large storage also have distinctly longer post-drought recovery times and are sensitive to long-term recharge deficits. Such a stress test modelling is useful to quantify the effect of prolonged recharge deficits in systems with long storage memory. Shorter and more event-specific stress test scenarios may be needed to identify tipping points in catchments' storage memory. However, interpretations of stress test results need to consider the representativeness of gauging stations in terms of bypassing subsurface flow and potential limitations of the models in representing extreme low flows.

As drought events can have different characteristics and have unique hydrological consequences among the diversity of catchments, stress tests should be designed in an event-specific way to develop worst-case scenarios with different timing, durations, and severities as precondition for different drought types (Stoelzle et al., 2018). In the future, for Swiss catchments such experiments could be combined with explicit considerations of changes in snowmelt-driven recharge and with particular alterations from human influences such as abstractions, reservoir operations, or specific low flow mitigation measures. Moreover, scenarios workshops that involve stakeholders in the development of scenarios and combined use of qualitative storylines and quantitative modelling tools could be mutually beneficial for water authorities, water managers, and scientists (Rinaudo et al., 2013).

Take-home messages

- Although the anthropogenic component in water resources is ubiquitous in Switzerland, research on controls of low flows has focused mostly on near-natural catchments. Abstractions and reservoir management may influence low flow situations, but disentangling climate forcing and human impacts is difficult. Quantitative information on flow regulation and water use are a key data requirement at this stage.
- Comparative regional studies linking flow indices to catchment characteristics have been informative regarding major differences among catchments. Snow and groundwater have been shown to provide storage for sustaining downstream flows in dry periods. Nevertheless, a better understanding of the distinct role of subsurface storage, headwater groundwater subsidies, and recharge processes is needed.
- Bedrock characteristics were identified to be a key to represent extended low flow situations following drainage of more productive aquifers of unconsolidated sediments adequately. Studies distinguish mainly between i) low storage/baseflow, rapidly draining and recovering systems typically found e.g. in crystalline background or Flysch environments and ii) high storage/baseflow, slowly draining and recovering systems as found for catchments dominated by the marine sandstones of the Obere Meeresmolasse. Conclusions on sensitivity with respect to low flows depend strongly on future event characteristics, i.e. short high intensity vs. long-term deficits.
- Synthetic scenario modelling proved to be an effective way to explore system characteristic differences in streamflow response and to eventually appraise catchments' sensitivity. It could be extended to test more systematically effects of recharge dynamics related to changes in snowmelt as well as the to-date largely unquantified human influences or the potential of mitigation measures as discussed for multi-purpose reservoirs.

7 Research gaps and open questions

This review demonstrates that research on climate change impacts in Switzerland has focused much less on low flow events than on general seasonal streamflow changes, i.e. regime shifts. In fact, only few specific low flow studies were available and often lacking data from latest low flow events, such as that in 2015. The event scale is important because in many rivers low flows may occur in any season and impacts on the various water uses and ecology will depend on characteristics such as the duration, volume, and recovery dynamics, rather than only on one specific critical water stage or streamflow rate. The lack of specific low flow studies is one reason why this review also draws substantially on studies from neighbouring countries and other mountain regions in the world.

Observed historical trends, in particular trends in summer low flow statistics, so far have been quite heterogeneous across Switzerland. A most recent assessment is not available. This gap suggests the high value of continued long-term streamflow monitoring and maintenance of reference stations with long records together with quality control and good metadata to allow attribution of causes. Station specific information from which specifically low flow assessments might benefit as criteria for station selection and for better result interpretation are: information on known human influences, any potential reasons for data inhomogeneities, assessments of low flow measurement reliability, and relevance of subsurface outflow. These aspects are mostly difficult to quantify, but even qualitative assessments or remarks from station operators (see, for instance, survey for cantonal stations in Naef and Margreth, 2017) as additional station metadata might help interpret regional low flow trend detection and attribution. Regular updates of trend analyses and event descriptions would be a key service to detect potential tipping points early and help judge how a new event such as that of 2018 compares to the long-term records. Regular analyses will provide important guidance for the required process studies and modelling discussed below.

There are a number of reasons for the lack of low flow assessments. Low flows tend to be influenced by abstractions. Without knowledge of the amount of water abstracted, stored, and discharged at any time it is difficult to untangle climate sensitivity. Many processes contribute to or mitigate low flows making a formalised attribution of trends to the causes difficult. Judging from the lack of available studies, indeed this has either not been attempted or not been feasible. Scenario projections with hydrological models driven by climate models have focused on the low flow season rather than on low flow events and their characteristics, among other reasons due to limitations of the modelled and downscaled climate forcing. But also the hydrological models have deficits regarding the representation of low flows as they were developed mainly to simulate the rainfall–runoff response rather than the storage–depletion behaviour. Both modelling parts in climate change assessments would benefit from improvements. Climate projections of extreme events may also remain highly uncertain due to uncertainties in the internal forcing and internal climate system variability. The resulting difficulty to conclude on expected propagations into changes in low flow characteristics such as extreme minimum flows, volumes, durations, and recovery potentials suggests that more complementary efforts might be dedicated towards the alternatives: (i) continuous monitoring and analysis of low flow events and their characteristics in observations and (ii) simulation experiments that target system understanding at the event scale.

As summer low flow events that are initiated by a lack of rain (and potentially increased evapotranspiration) are fed by stored water in the catchment, the volumes, dynamics, and interactions with streamflow need to be well understood and reliable models for scenario simulations available. This review identified key issues that require better understanding and improved representation of storage characteristics and response processes in models to simulate baseflow (i.e. contributions from delayed sources) more adequately and more catchment specific. The cross-seasonal link of snowpack and snowmelt rates to summer low flow through possible changes in groundwater recharge dynamics deserves to be more explicitly investigated for Switzerland. Pathways and delays in contributions to streamflow in particular have yet to be implemented and validated in most models. Studies targeting the understanding of the complex interacting processes and compensation effects that control low flows would benefit from a long-term commitment to research catchments in which all confounding influences on the water balance and runoff generation (or the lack of) can be quantified at any time and where coordinated monitoring networks of cryosphere and hydrosphere, i.e. glacier mass balance, snow water equivalent, streamflow, and groundwater heads, are well maintained. Well-designed monitoring networks that cover all types of hydrological regimes and hydrogeological settings in Switzerland and including paired surface water and groundwater stations alongside nested catchments with various streamflow regimes and geologies could beneficially contribute to more integrated research of hydrologists and hydrogeologists to gain a more holistic understanding of governing low flow processes and sensitivities to future changes at a regional scale. For a more widespread monitoring with not too much effort, considerably improved and easily accessible metadata on human influences and on catchment properties that characterise storages in the catchment should be collated and made available.

8 Concluding remarks and recommendations

The review revealed that low flows have not been given a high priority in past climate change assessments. Nevertheless, the general changes of seasonal streamflow provide a background change signal that in combination with rivers' streamflow sensitivity suggests that concerns over the reduction of future low flows in summer may be justified. The many competing direct influences of climate and human river flow regulation together with complex cross-seasonal recharge, storage, and release through groundwater–surface water coupling makes the attribution of the dominating effect of one such driver as well as the modelling of all relevant processes difficult. The use of hypothetical stress tests or storyline simulations is an effective way to gain a better understanding of system-characteristic differences in streamflow response and to eventually appraise catchments’ sensitivity. It could be extended to test more systematically the lacking knowledge on effects of recharge mechanism changes related to changes in snowmelt as well as the to-date largely unquantified human influences or consideration of mitigation measures as discussed for multi-purpose reservoirs. Progress will depend strongly on improved data.

References

Addor N., Rohrer M., Seibert J. 2016: Propagation of biases in climate models from the synoptic to the regional scale: Implications for bias adjustment. Journal of Geophysical Research: Atmospheres 121. https://doi.org/10.1002/2015JD024040

Addor N., Fischer E.M., 2015: The influence of natural variability and interpolation errors on bias characterization in RCM simulations. Journal of Geophysical Research: Atmospheres 120. https://doi.org/10.1002/2014JD022824

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. https://doi.org/10.1002/2014WR015549

Addor N., Seibert J. 2014: Bias correction for hydrological impact studies–beyond the daily perspective. Hydrological Processes 28: 4823–4828. https://doi.org/10.1002/hyp.10238

Allen D.M., Whitfield P.H., Werner A. 2010: Groundwater level responses in temperate mountainous terrain: Regime classification, and linkages to climate and streamflow. Hydrological Processes 24: 3392–3412. https://doi.org/10.1002/hyp.7757

Ameli A.A., Gabrielli C., Morgenstern U., McDonnell J.J. 2018: Groundwater subsidy from headwaters to their parent water watershed: A combined field-modeling approach. Water Resources Research, https://doi.org/10.1029/2017WR022356

Aschwanden H., Kan C. 1999a: Die Abflussmenge Q347. Eine Standortbestimmung. Hydrologische Mitteilungen der Landeshydrologie und -geologie Nr. 27. Bern.

Aschwanden H., Kan C. 1999b: Low flow – Elements Used for Determining Q 347 Flow Rate. Plate 5.8. In: Hydrological Atlas of Switzerland. Federal Office for the Environment, Bern.

Aschwanden H. 1992: Die Niedrigwasserabflussmenge Q347 Bestimmung und Abschätzung in alpinen schweizerischen Einzugsgebieten. Hydrologische Mitteilung der Landeshydrologie und -geologie 18. Bern.

Bard A., Renard B., Lang M., Giuntoli I., Korck J., Koboltschnig G., Janža M., D’Amico M., Volken D. 2015: Trends in the hydrologic regime of Alpine rivers. Journal of Hydrology 529: 1823–1837. https://doi.org/10.1016/j.jhydrol.2015.07.052

Bard A., Renard B., Lang M., Janza M., D’Amico M., Volken D., 2011: The AdaptAlp Dataset. Description, guidance and analyses. AdaptAlp WP 4 Report.

Barnett T.P., Pierce D.W., Hidalgo H.G., Bonfils C., Santer B.D., Das T., Bala G., Wood A.W. Nozawa, T., Mirin A.A., Cayan D.R., Dettinger M.D. 2008: Human-Induced Changes in the Hydrology of the Western United States. Science 319: 1080–1084.

Barnett T.P., Adam J.C., Lettenmaier D.P. 2005: Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438: 303–309.

Barnhart T.B., Molotch N.P., Livneh B., Harpold A.A., Knowles J.F., Schneider D. 2016: Snowmelt rate dictates streamflow. Geophysical Research Letters 43: 8006–8016.

Barthel R., 2014: HESS Opinions “Integration of groundwater and surface water research: An interdisciplinary problem?” Hydrology and Earth System Sciences 18: 2615–2628.

Bastola S., Murphy C., Sweeney J. 2011: The role of hydrological modelling uncertainties in climate change impact assessments of Irish river catchments. Advances in Water Resources 34: 562–576.

Baumgartner M., Devanthéry D., Kummer M., 2007: Water Withdrawal and Return. Plate 5. 10. In: Hydrological Atlas of Switzerland. Federal Office for the Environment.

Beaulieu M., Schreier H., Jost G. 2012: A shifting hydrological regime: a field investigation of snowmelt runoff processes and their connection to summer base flow, Sunshine Coast, British Columbia. Hydrological Processes 26: 2672–2682. https://doi.org/10.1002/hyp.9404

Belz J.U., Brahmer G., Buiteveld H., Engel H., Grabher R., Hodel H., Krahe P., Lammersen R., Larina

M., Mendel H., Meuser A., Plonka B., Pfister L., Vuuren W. Van 2007: Das Abflussregime des Rheins und seiner Nebenflüsse Analyse, Veränderungen, Trends. CHR report No. I-22. International Commission for the Hydrology of the Rhine basin (CHR), Lelystad.

Bernhard L., Zappa M. 2012: Schlussbericht CCHydrologie. Teilprojekt WHH-CH-Hydro. Natürlicher Wasserhaushalt der Schweiz und ihrer bedeutendsten Grosseinzugsgebiete. Birmensdorf.

Bernhard L., Zappa M., Kotlarski S., Paul F., Giuz G.I., Zürich U., Viviroli D. Stähli M., Ossiaa M., Fundel F., Hess S. 2011: Klimaänderung und natürlicher Wasserhaushalt der Grosseinzugsgebiete Alpenrhein und Engadin – Technical Report. AdaptAlp Project.

Birsan M., Molnar P., Burlando P., Pfaundler M. 2005: Streamflow trends in Switzerland. Journal of Hydrology 314: 312–329. https://doi.org/10.1016/j.jhydrol.2005.06.008

Björnsen Gurung A., Stähli M., 2014: Wasserressourcen der Schweiz Dargebot und Nutzung – heute und morgen. NFP 61 – thematische Synthese 1 im Rahmen des Nationalen Forschungsprogramms NFP 61 «Nachhaltige Wassernutzung». Bern.

Bloomfield J.P., Marchant B.P., Bricker S.H., Morgan R.B. 2015: Regional analysis of groundwater droughts using hydrograph classification. Hydrology and Earth System Sciences 19: 4327–4344. https://doi.org/10.5194/hess-19-4327-2015

Blöschl G., Viglione A., Merz R., Parajka J., Salinas J.L., Schöner W. 2011: Auswirkungen des Klimawandels auf Hochwasser und Niederwasser. Österreichische Wasser- und Abfallwirtschaft 2011: 21–30.

Bocchiola D. 2014:. Long term (1921–2011) hydrological regime of Alpine catchments in Northern Italy. Advances in Water Resources 70, 51–64. https://doi.org/10.1016/j.advwatres.2014.04.017

Bosshard T., Carambia M., Goergen K., Kotlarski S., Krahe P., Zappa M., Schär C. 2013: Quantifying uncertainty sources in an ensemble of hydrological climate-impact projections. Water Resources Research 49: 1523–1536. https://doi.org/10.1029/2011WR011533

Bosshard T., Kotlarski S., Ewen T., Schär C. 2011a: Spectral representation of the annual cycle in the climate change signal. Hydrology and Earth System Sciences 15: 2777–2788.

Bosshard T., Kotlarski S., Ewen T., Schär C. 2011b: Klimaszenarien für Klimaimpaktstudien in der Schweiz. CCHydro Projekt Klimaänderung und Wasserkraftnutzung. Grundlagenmodul 1.

Brunner M.I., Speerli J., Björnsen-Gurung A., Kytzia S., Bieler S. 2018: Potential of multi-purpose reservoirs for the reduction of water scarcity: A multi-modular assessment framework. Geophysical Research Abstracts 20: EGU2018-5956.

Bundesrat 1947. Botschaft des Bundesrates an die Bundesversammlung über außerordentliche Maßnahmen zur Milderung der Notlage in den Trockengebieten (vom 26. September 1947). Bundesblatt XCIX/39: 189–211, Bern.

Burn D.H., Hannaford J., Hodgkins G.A., Whitfield P.H., Thorne R., Marsh T. 2012: Reference hydrologic networks II . Using reference hydrologic networks to assess climate-driven changes in streamflow Reference hydrologic networks II . Using reference hydrologic networks to assess climate-driven changes in streamflow. Hydrological Sciences Journal 57: 1580–1593.

Buttle J.M. 2018: Mediating stream baseflow response to climate change: The role of basin storage. Hydrological Processes 32: 363–378. https://doi.org/10.1002/hyp.11418

Buttle J.M. 2016: Dynamic storage: a potential metric of inter-basin differences in storage properties. Hydrological Processes 30: 4644–4653. https://doi.org/10.1002/hyp.10931

BUWAL, BWG, MeteoSchweiz 2004: Auswirkungen des Hitzesommers 2003 auf die Gewässer. Schriftenreihe Umwelt Nr. 369. Bern.

Calanca P. 2007: Climate change and drought occurrence in the Alpine region: How severe are becoming the extremes ? Global and Planetary Change 57: 151–160.

Cannon A. 2016: Multivariate Bias Correction of Climate Model Output: Matching Marginal Distributions and Intervariable Dependence Structure. Journal of Climate 29: 7045–7064.

CH2018, 2018: CH2018 – Climate Scenarios for Switzerland, Technical Report, National Centre for Climate Services, Zurich. https://doi.org/10.1038/nn1259

CH2011, 2011: Swiss Climate Change Scenarios CH2011. Zurich. http://www.ch2011.ch/

Chaix O., Wehse H., Gander Y., Zahner S. 2016: Bestimmung von Regionen mit Handlungsbedarf bei Trockenheit. Expertenbericht zum Umgang mit lokaler Wasserknappheit in der Schweiz. Bericht Nr. 7023.13-BP012i, Hunziker Betatech AG, Bern.

Christensen J.H., Krishna Kumar K., Aldrian E., An S.-I., Cavalcanti I.F.A., de Castro M., Dong W., Goswami P., Hall A., Kanyanga J.K., Kitoh A., Kossin J., Lau N.-C., Renwick J., Stephenson D.B., Xie S.-P., Zhou T. 2013: Climate Phenomena and their Relevance for Future Regional Climate Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Clark M.P., Wilby R.L., Gutmann E.D., Vano J.A., Gangopadhyay S., Wood A.W., Fowler H.J., Prudhomme C., Arnold J.R., Brekke L.D. 2016: Characterizing Uncertainty of the Hydrologic Impacts of Climate Change. Current Climate Change Reports 2: 55–64.

Clow D.W., Schrott L., Webb R., Campbell D.H., Torizzo A., Dornblaser M. 2003: Ground Water Occurrence and Contributions to Streamflow in an Alpine Catchment, Colorado Front Range. Ground Water 41: 937–950.

Cooper M.G., Schaperow J.R., Cooley S.W., Alam S., Smith L.C., Lettenmaier D.P. 2018: Climate Elasticity of Low Flows in the Maritime Western US Mountains. Water Resources Research 54: 5602–5619.

Cooper M.G., Nolin A.W., Safeeq M. 2016: Testing the recent snow drought as an analog for climate warming sensitivity of Cascades snowpacks. Environmental Research Letters 11(8): 084009.

Coron L., Andre V., Perrin C., Lerat J., Vaze J., Bourqui M., Hendrickx F. 2012: Crash testing hydrological models in contrasted climate conditions: An experiment on 216 Australian catchments. Water Resources Research 48: W05552. https://doi.org/10.1029/2011WR011721

Demirel M.C., Booij M.J., Hoekstra A.Y. 2013a: Impacts of Climate Change on the Seasonality of Low Flows in 134 Catchments in the River Rhine Basin Using an Ensemble of Bias- Corrected Regional Climate Simulations. Hydrology and Earth System Sciences 17: 4241–4257.

Demirel M.C., Booij M.J., Hoekstra A.Y. 2013b: Effect of different uncertainty sources on the skill of 10 day ensemble low flow forecasts for two hydrological models. Water Resources Research 49: 4035–4053. https://doi.org/10.1002/wrcr.20294

Déry S.J., Stahl K., Moore R.D., Whitfield P.H., Menounos B., Burford J.E. 2009: Detection of runoff timing changes in pluvial, nival, and glacial rivers of western Canada. Water Resources Research 45: W04426. https://doi.org/10.1029/2008WR006975

Dessai S., Hulme M. 2004: Does climate adaptation policy need probabilities ? Climate policy 4: 107–128.

Dübendorfer C., Tratschin R., Urfer D., Zahner S., Zysset A. 2016: Umgang mit Wasserressourcen in Ausnahmesituationen. Expertenbericht zum Umgang mit lokaler Wasserknappheit in der Schweiz. Bericht im Auftrag des BAFU, Ernst Baser + Partner (EBP) / RWB Jura SA.

EAWAG 2011: Factsheet: Hydropower and ecology. Swiss Federal Institute of Aquatic Science and Technology (EAWAG), Dübendorf.

Ehret U., Zehe E., Wulfmeyer V., Liebert J. 2012: HESS Opinions “Should we apply bias correction to global and regional climate model data?” Hydrology and Earth System Sciences 16: 3391–3404.

Farinotti D., Usselmann S., Huss M., Bauder A., Funk M. 2012: Runoff evolution in the Swiss Alps: projections for selected high-alpine catchments based on ENSEMBLES scenarios. Hydrological Processes 26: 1909–1924. https://doi.org/10.1002/hyp.8276

Fatichi S., Rimkus S., Burlando P., Bordoy R., Molnar P. 2015: High-resolution distributed analysis of climate and anthropogenic changes on the hydrology of an Alpine catchment. Journal of Hydrology 525: 362–382. https://doi.org/10.1016/j.jhydrol.2015.03.036

Fatichi S., Rimkus S., Burlando P., Bordoy R. 2014: Does internal climate variability overwhelm climate change signals in stream flow? The upper Po and Rhone basin case studies. Sci. Total Environ. 493: 1171–1182. https://doi.org/10.1016/j.scitotenv.2013.12.014

Feigenwinter I., Kotlarski S., Casanueva A., Fischer A.M., Schwierz C., Liniger M.A. 2018: Exploring quantile mapping as a tool to produce user-tailored climate scenarios for Switzerland. Technical Report MetoSwiss No. 270.

Fischer A.M., Weigel A.P., Buser C.M., Knutti R., Künsch H.R., Liniger M.A., SChär C., Appenzeller C. 2012: Climate change projections for Switzerland based on a Bayesian multi-model approach. International Journal of Climatology 32: 2348–2371. https://doi.org/10.1002/joc.3396

Fischer B.M.C., Rinderer M., Schneider P., Ewen T., Seibert J. 2015: Contributing sources to base flow in pre-alpine headwaters using spatial snapshot sampling. Hydrological Processes 29: 5321–5336. https://doi.org/10.1002/hyp.10529

Fischer E.M., Beyerle U., Knutti R. 2013: Robust spatially aggregated projections of climate extremes. Nature Climate Change 3: 1–6. https://doi.org/10.1038/nclimate2051

Floriancic M.G., van Meerveld H.J., Smoorenburg M., Margreth M. 2018. Spatio-temporal variability in contributions to low flows in the high Alpine Poschiavino catchment. Hydrological Processes https://doi.org/10.1002/hyp.13302

FOEN 2017: Januar 2017: Niedrigwasser mit Vereisung. https://www.bafu.admin.ch/bafu/de/home/themen/wasser/dossiers/niedrigwasser-januar-2017.html [WWW Document].

FOEN 2016: Hitze und Trockenheit im Sommer 2015. Auswirkungen auf Mensch und Umwelt. Umwelt-Zustand Nr. 1629. Bern.

FOEN 2012a: Umgang mit lokaler Wasserknappheit in der Schweiz. Bericht des Bundesrates zum Postulat „Wasser und Landwirtschaft. Zukünftige Herausforderungen“ (Postulat 10.353 von Nationalrat Hansjörg Walter vom 17. Juni 2010). Bern.

FOEN 2012b: Effects of Climate Change on Water Resources and Waters. Synthesis report on “Climate Change and Hydrology in Swizuerland” (CCHydro) project. Umwelt-Wissen No 1217. Bern.

Forzieri G., Feyen L., Rojas R., Flörke M., Wimmer F., Bianchi A. 2014: Ensemble projections of future streamflow droughts in Europe. Hydrology and Earth System Sciences 18: 85–108.

Fowler H.J., Blenkinsop S., Tebaldi C. 2007: Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. International Journal of Climatology 27: 1547–1578. https://doi.org/10.1002/joc

Fowler K., Peel M., Western A., Zhang L. 2018: Improved Rainfall-Runoff Calibration for Drying Climate: Choice of Objective Function. Water Resour. Publ. Highl. Ranch, CO, USA 54. https://doi.org/10.1029/2017WR022466

Fuhrer J., Jasper K. 2012: Demand and Supply of Water for Agriculture: Influence of Topography and Climate in Pre-Alpine, Mesoscale Catchments. Natural Resources 2012: 145–155.

Fuhrer J., Jasper K., 2009: Bewässerunsgbedürftigkeit von Acker- und Grasland im heutigen Klima. AGRARforschung 16: 396–401.

Giuntoli I., Renard B., Vidal J., Bard A. 2012: Low flows in France and their relationship to large-scale climate indices. Journal of Hydrology 482: 105–118. https://doi.org/10.1016/j.jhydrol.2012.12.038

Godsey S.E., Kirchner J.W., Tague C.L. 2014: Effects of changes in winter snowpacks on summer low flows: case studies in the Sierra Nevada, California, USA. Hydrological Processes 28: 5048–5064. https://doi.org/10.1002/hyp.9943

Görgen K., Beersma J., Brahmer G., Buiteveld H., Carambia M., de Keizer O., Krahe P., Nilson E., Lammersen R., Perrin C., Volken D. 2010: Assessment of Climate Change Impacts on Discharge in the Rhine River Basin: Results of the RheinBlick2050 Project. CHR report No. I-23. International Commission for the Hydrology of the Rhine basin (CHR), Lelystad.

Gosling S.N., Zaherpour J., Mount N.J., Hattermann F.F., Dankers R., Arheimer B., Breuer L. 2017: A comparison of changes in river runoff from multiple global and catchment-scale hydrological models under global warming scenarios of 1 °C, 2 °C and 3 °C. Climatic Change 141: 577–595.

Griessinger N., Seibert J., Magnusson J., Jonas T. 2016: Assessing the benefit of snow data assimilation for runoff modeling in Alpine catchments. Hydrology and Earth System Sciences 20: 3895–3905. https://doi.org/10.5194/hess-20-3895-2016

Gustard A., Demuth S. 2008: Manual on Low-flow Estimation and Prediction. Operational Hydrology Report No. 50. WMO-No. 1029. Geneva.

Hakala K., Addor N., Teutschbein C., Vis M., Dakhlaoui H., Seibert J. in print: Hydrological climate change impact modeling. In: Maurice P. (Ed.): Encyclopedia of Water: Science, Technology, and Society.

Hall F.R. 1968: Base-Flow Recessions—A Review. Water Resources Research 4: 973–983.

Hänggi P., Weingartner R. 2012: Variations in Discharge Volumes for Hydropower Generation in Switzerland. Water Resources Management 26: 1231–1252.

Hänggi P., Weingartner R. 2011: Inter-annual variability of runoff and climate within the Upper Rhine River basin, 1808–2007. Hydrological Sciences Journal 56: 34–50.

Hannaford J., Buys G., Stahl K., Tallaksen L.M. 2013. The influence of decadal-scale variability on trends in long European streamflow records. Hydrology and Earth System Sciences 17: 2717–2733. https://doi.org/10.5194/hess-17-2717-2013

Hanzer F., Förster K., Nemec J., Strasser U. 2018: Projected cryospheric and hydrological impacts of 21st century climate change in the Ötztal Alps (Austria) simulated using a physically based approach. Hydrology and Earth System Sciences 22: 1593–1614.

Harrington J.S., Mozil A., Hayashi M., Bentley L.R. 2018: Groundwater flow and storage processes in an inactive rock glacier. Hydrological Processes https://doi.org/10.1002/hyp.13248

Haslinger K., Blöschl G. 2017: Space-Time Patterns of Meteorological Drought Events in the European Greater Alpine Region Over the Past 210 Years. Water Resources Research 53: 9807–9823.

Helbling A., Kan C., Marti P. 2007: Low Flow – Minimum Mean Discharge over Several Days. Plate 5.11. In: Hydrological Atlas of Switzerland. Federal Office for the Environment (FOEN), Bern.

Hisdal H., Tallaksen L.M., Clausen B., Peters E. 2004: Hydrological Drought Characteristics. In: Tallaksen L.M., van Lanen H.A.J. (Eds.): Hydrological Drought Processes and Estimation Methods for Streamflow and Groundwater. Developments in Water Sciences 48. Elsevier B.V., Amsterdam / Oxford.

Honti M., Scheidegger A., Stamm C. 2014: The importance of hydrological uncertainty assessment methods in climate change impact studies. Hydrology and Earth System Sciences 18: 3301–3317. https://doi.org/10.5194/hess-18-3301-2014

Hood J.L., Hayashi M. 2015: Characterization of snowmelt flux and groundwater storage in an alpine headwater basin. Journal of Hydrology 521: 482–497.

Hunkeler D., Möck C., Käser D., Brunner P. 2014: Klimaeinflüsse auf Grundwassermengen. Aqua Gas 2014: 42–49.

Huntington J.L., Niswonger R.G. 2010: Role of surface-water and groundwater interactions on projected summertime streamflow in snow dominated regions: An integrated modeling approach. Water Resources Research 48. https://doi.org/10.1029/2012WR012319

Huss M., Hock R. 2018: Global-scale hydrological response to future glacier mass loss. Nature Climate Change 8(2): 135.

Huss M., Bookhagen B., Huggel C., Jacobsen D., Bradley R.S., Clague J.J., Vuille M. 2017: Toward mountains without permanent snow and ice. Earth’s Future 5. https://doi.org/10.1002/eft2.207

Huss M., Zemp M., Joerg P.C., Salzmann N. 2013: High uncertainty in 21st century runoff projections from glacierized basins. Journal of Hydrology 510: 35–48.

Huss M. 2012: Extrapolating glacier mass balance to the mountain-range scale: the European Alps 1900

– 2100. The Cryosphere 6: 713–727. https://doi.org/10.5194/tc-6-713-2012

Huss M. 2011: Present and future contribution of glacier storage change to runoff from macroscale drainage basins in Europe. Water Resources Research 47. https://doi.org/10.1029/2010WR010299

Hydro-CH2018 Wasserspeicher, 2017: Projekt-Flyer: Schützen Mehrzweckspeicher zukünftig vor Trockenheit ?

ICPR 2018: Bestandsaufnahme zu den Niedrigwasserverhältnissen am Rhein. ICPR report no 248. International Commission for the Protection of the Rhine (ICPR), Koblenz.

IPCC 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (Eds.)]. IPCC, Geneva.

IPCC 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field C.B., Barros V., Stocker T.F., Qin D., Dokken D.J., Ebi K.L., Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge / New York.

Ivanov M.A., Kotlarski, S., 2017: Assessing distribution-based climate model bias correction methods over an alpine domain: added value and limitations. International Journal of Climatology 37: 2633–2653. https://doi.org/10.1002/joc.4870

Jasechko S., Kirchner J.W., Welker J.M., McDonnell J.J. 2016: Substantial proportion of global streamflow less than three months old. Nature Geoscience 9: 126–129.

Jefferson A.J. 2011: Seasonal versus transient snow and the elevation dependence of climate sensitivity in maritime mountainous regions. Geophysical Research Letters 38: L16402.

Jenicek M., Seibert J., Staudinger M. 2018: Modeling of future changes in seasonal snowpack and impacts on summer low flows in alpine catchments. Water Resources Research 54: 538–556.

Jenicek M., Seibert J., Zappa M., Staudinger M., Jonas T. 2016. Importance of maximum snow accumulation for summer low flows in humid catchments. Hydrology and Earth System Sciences 20: 859–874. https://doi.org/10.5194/hess-20-859-2016

Jones J.A. 2011: Hydrologic responses to climate change: considering geographic context and alternative hypotheses. Hydrological Processes 25: 1996–2000. https://doi.org/10.1002/hyp.8004

Jörg-Hess S., Kempf S.B., Fundel F., Zappa M. 2015: The benefit of climatological and calibrated reforecast data for simulating hydrological droughts in Switzerland. Meteorological Applications 22: 444–458. https://doi.org/10.1002/met.1474

Jörg-Hess S. 2014: Towards Operational Monthly Predictions of Critical Water Resources Anomalies in the Swiss Alps. ETH Zurich. https://doi.org/doi.org/10.3929/ethz-a-010259280

Käser D., Hunkeler D. 2016: Contribution of alluvial groundwater to the outflow of mountainous catchments. Water Resources Research 52: 680–697.

Khaliq M.N., Ouarda T.B.M.J., Gachon P., Sushama L., St-Hilaire A. 2009: Identification of hydrological trends in the presence of serial and cross correlations : A review of selected methods and their application to annual flow regimes of Canadian rivers. Journal of Hydrology 368, 117–130. https://doi.org/10.1016/j.jhydrol.2009.01.035

Khaliq M.N., Ouarda T.B.M.J., Gachon P., Sushama L. 2008: Temporal evolution of low-flow regimes in Canadian rivers. Water Resources Research 44: W08436.

Kirchner J.W. 2009: Catchments as simple dynamical systems: Catchment characterization, rainfall-runoff modeling, and doing hydrology backward. Water Resources Research 45: W02429.

Klein G., Vitasse Y., Rixen C., Marty C., Rebetez M. 2016: Shorter snow cover duration since 1970 in the Swiss Alps due to earlier snowmelt more than to later snow onset. Climatic Change 139: 637–649. https://doi.org/10.1007/s10584-016-1806-y

Kling H., Stanzel P., Fuchs M., Nachtnebel H.-P. 2015: Performance of the COSERO precipitation–runoff model under non-stationary conditions in basins with different climates. Hydrological Sciences Journal 60, 1374–1393. https://doi.org/10.1080/02626667.2014.959956

KLIWA 2018: Niedrigwasser in Süddeutschland. Analysen, Szenarien und Handlungsempfehlungen. KLIWA-Berichte, Heft 23. Karlsruhe / Hof / Mainz.

KLIWA 2017: Monitoringbericht 2016. Klimawandel in Süddeutschland. Veränderungen von meteorologischen und hydrologischen Kenngrößen. Klimamonitoring im Rahmen der Kooperation KLIWA. Karlsruhe / Hof / Mainz.

KLIWA 2011: Monitoringbericht 2011. Klimawandel in Süddeutschland. Veränderungen von meteorologischen und hydrologischen Kenngrößen. Klimamonitoring im Rahmen der Kooperation KLIWA. Karlsruhe / Hof / Mainz.

Kobierska F., Jonas T., Kirchner J.W., Bernasconi S.M. 2015: Linking baseflow separation and groundwater storage dynamics in an alpine basin (Dammagletscher, Switzerland). Hydrology and Earth System Sciences 19: 3681–3693. https://doi.org/10.5194/hess-19-3681-2015

Kobierska F., Jonas T., Zappa M., Bavay M., Magnusson J., Bernasconi S.M. 2013: Future runoff from a partly glacierized watershed in Central Switzerland: A two-model approach. Advances in Water Resources 55: 204–214. https://doi.org/10.1016/j.advwatres.2012.07.024

Köplin N., Rössler O., Schädler B., Weingartner R. 2014: Robust estimates of climate-induced hydrological change in a temperate mountainous region. Climatic Change 122: 171–184.

Köplin N., Schädler B., Viviroli D., Weingartner R. 2012: Relating climate change signals and physiographic catchment properties to clustered hydrological response types. Hydrology and Earth System Sciences 16: 2267–2283. https://doi.org/10.5194/hess-16-2267-2012

Köplin N., Schädler B., Viviroli D., Weingartner R. 2011: Klimaänderung und Wasserhaushalt in sensitiven Bilanzierungsgebieten. Schlussbericht CCHydro – Modul 3.

Köplin N., Viviroli D., Schädler B., Weingartner R. 2010: How does climate change affect mesoscale catchments in Switzerland ? – a framework for a comprehensive assessment. Advances in Geosciences 27: 111–119. https://doi.org/10.5194/adgeo-27-111-2010

Krahe P., Nilson E., Knoche M., Ebner Von Eschenbach A.D. 2016: Modeling human-water-systems: Towards a comprehensive and spatially distributed assessment of co-evolutions for river basins in central Europe. IAHS-AISH Proc. Reports 373: 119–123.

Krahe P., Bosshard T., Carambia M., Zappa M., Nilson E., Volken D. 2011: Water Regime in the Alpine Space: The Alpine Rhine River Basin. AdaptAlp WP 4 Regional Report.

Kronholm S.C., Capel P.D. 2015: A comparison of high-resolution specific conductance-based end-member mixing analysis and a graphical method for baseflow separation of four streams in hydrologically challenging agricultural watersheds. Hydrological Processes 29, 2521–2533. https://doi.org/10.1002/hyp.10378

Krysanova V., Donnelly C., Gelfan A., Gerten D., Arheimer B., Hattermann F., Kundzewicz Z.W. 2018: How the performance of hydrological models relates to credibility of projections under climate change. Hydrological Sciences Journal 63: 696–720.

Lanz K., Rahn E., Siber R., Stamm C. 2014: Bewirtschaftung der Wasserressourcen unter steigendem Nutzungsdruck. NFP 61 – Thematische Synthese 2 im Rahmen des Nationalen Forschungsprogramms NFP 61 «Nachhaltige Wassernutzung». Bern.

Laternser M., Schneebeli M. 2003: Long-term snow climate trends of the Swiss Alps (1931–99). International Journal of Climatology 23: 733–750. https://doi.org/10.1002/joc.912

Leitungsgruppe NFP 61 2015a: Nachhaltige Wassernutzung in der Schweiz. Gesamtsynthese des Nationalen Forschungsprogramms NFP 61 «Nachhaltige Wassernutzung». Bern. https://doi.org/10.3218/3612-1

Leitungsgruppe NFP 61 2015b: Faktenblatt: Ergebnisse und Empfehlungen des Nationalen Forschungsprogrammes « Nachhaltige Wassernutzung » NFP 61.

LfU 2014: Die Entwicklung der Niedrigwasserabflüsse in Bayern. Bayerisches Landesamt für Umwelt (LfU), Augsburg.

Lloyd-Hughes B. 2014: The impracticality of a universal drought definition. Theoretical and Applied Climatology 117: 607–611. https://doi.org/10.1007/s00704-013-1025-7

Luce C.H., Holden Z.A., 2009: Declining annual streamflow distributions in the Pacific Northwest United States, 1948–2006. Geophysical Research Letters 36. https://doi.org/10.1029/2009GL039407

Lundberg A., Ala-Aho P., Eklo O., Klöve B., Kværner J., Stumpp C. 2016: Snow and frost: Implications for spatiotemporal infiltration patterns - a review. Hydrological Processes 30– 1230–1250.

Maraun D., Shepherd T.G., Widmann M., Zappa G., Walton D., Gutiérrez J.M., Hagemann S., Richter I., Soares P.M.M., Hall A., Mearns L.O. 2017: Towards process-informed bias correction of climate change simulations. Nature Climate Change 7– 764–773.

Maraun D. 2016: Bias Correcting Climate Change Simulations - a Critical Review. Current Climate Change Reports 2: 211–220. https://doi.org/10.1007/s40641-016-0050-x

Maraun D. 2013: Bias Correction, Quantile Mapping, and Downscaling: Revisiting the Inflation Issue. Journal of Climate 26: 2137–2143. https://doi.org/10.1175/JCLI-D-12-00821.1

Margot A., Sigg R., Schädler B., Weingartner R. 1992: Influence on Rivers by Water Power Stations and Lakes. Plate 5.3. In: Hydrological Atlas of Switzerland. Federal Office for the Environment, Bern.

Margreth M., Naef, F., Scherrer, S. 2013: Pilotstudie zur Anwendung von Abflussprozesskarten im Niedrigwasserbereich.

Markovich K.H., Maxwell R.M., Fogg G.E. 2016: Hydrogeological response to climate change in alpine hillslopes. Hydrological Processes 30: 3126–3138. https://doi.org/10.1002/hyp.10851

Marti P., Kan C. 2003: Vergleich der Trockenjahre 1947 und 2003 - ein Anwendungsbeispiel der Niedrigwasser-Datenbank NQStat. Wasser Energie Luft 95: 333–336.

Marty C., Meister R. 2012: Long-term snow and weather observations at Weissfluhjoch and its relation to other high-altitude observatories in the Alps. Theoretical and Applied Climatology 110: 573–583. https://doi.org/10.1007/s00704-012-0584-3

Marty C. 2008: Regime shift of snow days in Switzerland. Geophysical Research Letters 35: L12501. https://doi.org/10.1029/2008GL033998

Masato G., Hoskins B.J., Woollings T. 2013. Winter and Summer Northern Hemisphere Blocking in CMIP5 Models. Journal of Climate 26: 7044–7059. https://doi.org/10.1175/JCLI-D-12-00466.1

McNamara J.P., Tetzlaff D., Bishop K., Soulsby C., Seyfried M., Peters N.E., Aulenbach B.T., Hooper R. 2011: Storage as a Metric of Catchment Comparison. Hydrological Processes 25: 3364–3371.

McPhillips L.E., Chang H., Chester M.V, Depietri Y., Friedman E., Grimm N.B., Kominoski J.S., Mcphearson T., Méndez-lázaro P., Rosi E.J., Shiva J.S. 2018: Defining Extreme Events: A Cross-Disciplinary Review. Earth's Future 6. https://doi.org/10.1002/eft2.304

Meeks J., Moeck C., Brunner P., Hunkeler D. 2017: Infiltration under snow cover: Modeling approaches and predictive uncertainty. Journal of Hydrology 546: 16–27.

Melsen L., Addor N., Mizukami N., Newman A., Torfs P., Clark M., Uijlenhoet R., Teuling R. 2018: Mapping (dis) agreement in hydrologic projections. Hydrology and Earth System Sciences 22: 1775–1791. https://doi.org/10.5194/hess-22-1775-2018

Mendoza P.A., Clark M.P., Mizukami N., Gutmann E.D., Arnold J.R., Brekke L.D., Rajagopalan B. 2016: How do hydrologic modeling decisions affect the portrayal of climate change impacts ? Hydrological Processes 30: 1071–1095. https://doi.org/10.1002/hyp.10684

Mendoza P.A., Clark M.P., Mitzukami N., Newman A.J., Barlage M., Gutman E.D., Rasmussen R.M., Rajagopalan B., Brekke L.D., Arnold J.R. 2015: Effects of Hydrologic Model Choice and Calibration on the Portrayal of Climate Change Impacts. Journal of Hydrometeorology 16: 762–780. https://doi.org/10.1175/JHM-D-14-0104.1

Merz B., Vorogushyn S., Uhlemann S., Delgado J., Hundecha Y. 2012. HESS Opinions "More efforts and scientific rigour are needed to attribute trends in flood time series." Hydrology and Earth System Sciences 16: 1379–1387. https://doi.org/10.5194/hess-16-1379-2012

Merz R., Parajka J., Blöschl G. 2011: Time stability of catchment model parameters : Implications for climate impact analyses. Water Resources Research 47: W02531.

MeteoSchweiz 2016: Analyse der Nutzerbedürfnisse zu nationalen Klimaszenarien. Zurich.

Meyer J., Kohn I., Stahl K., Hakala K., Seibert J., Cannon A.J. in review: Effects of univariate and multivariate bias correction on hydrological impact projections in alpine catchments. Hydrology and Earth System Sciences Discussion, https://doi.org/https://doi.org/10.5194/hess-2018-317

Meyer R. 2012: Die Auswirkungen der projizierten Klimaänderung auf Sommerniedrigwasser im Schweizer Mittelland basierend auf einer multi-variablen Kalibrierung des hydrologischen Modellsystems PREVAH. Bern.

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

Meyer R., Schädler B., Viviroli D., Weingartner R. 2011b: Klimaänderung und Niedrigwasser. Auswirkungen der Klimaänderung auf die Niedrigwasserverhältnisse im Schweizer Mittelland für 2021-2050 und 2070-2099. Schlussbericht CCHydro – Modul 4.

Milano M., Reynard E., Bosshard N., Weingartner R. 2015a: Simulating future trends in hydrological regimes in Western Switzerland. Journal of Hydrology Regional Studies 4: 748–761.

Milano M., Reynard E., Köplin N., Weingartner R. 2015b: Climatic and anthropogenic changes in Western Switzerland: Impacts on water stress. Sci. Total Environ. 536: 12–24.

Miller M.P., Buto S.G., Susong D.D., Rumsey C.A. 2016: The importance of base flow in sustaining surface water flow in the Upper Colorado River Basin. Water Resources Research 52: 3547–3562. https://doi.org/10.1002/2015WR017963.Received

Moeck C., von Freyberg J., Schirmer M. 2018: Groundwater recharge predictions in contrasted climate: The effect of model complexity and calibration period on recharge rates. Environmental Modelling and Software 103: 74–89. https://doi.org/10.1016/j.envsoft.2018.02.005

Moeck C., Brunner P., Hunkeler D. 2016: The influence of model structure on groundwater recharge rates in climate-change impact studies. Hydrogeology Journal 24: 1171–1184.

Montanari A., Young G., Savenije H.H.G., Hughes D., Wagener T., Ren L.L., Koutsoyiannis D., Cudennec C., Toth E., Grimaldi S., Blöschl G., Sivapalan M., Beven K., Gupta H., Hipsey M., Schaefli, B., Arheimer, B., Boegh, E., Schymanski, S.J., Di Baldassarre, G., Yu, B., Hubert, P., Huang Y., Schumann A., Post D., Srinivasan V., Harman C., Thompson S., Rogger M., Viglione A., McMillan H., Characklis G., Pang Z., Belyaev V. 2013: "Panta Rhei—Everything Flows": Change in hydrology and society—The IAHS Scientific Decade 2013–2022. Hydrological Sciences Journal 58: 1256–1275. https://doi.org/10.1080/02626667.2013.809088

Moon H., Gudmundsson L., Seneviratne S.I. 2018: Drought Persistence Errors in Global Climate Models. Journal of Geophysical Research: Atmospheres 123. https://doi.org/10.1002/2017JD027577

Mote P.W., Rupp D.E., Li S., Sharp D.J., Otto F., Uhe P.F., Xiao M., Lettenmaier D.P., Cullen H., Allen M.R. 2016: Perspectives on the causes of the exceptionally low 2015 snowpack in the western United States. Geophysical Research Letters 43: 10980–10988.

Musselman K.N., Clark M.P., Liu C., Ikeda K., Rasmussen R. 2017a: Slower snowmelt in a warmer world. Nature Climate Change 7. https://doi.org/10.1038/nclimate3225

Musselman K.N., Molotch N.P., Margulis S.A. 2017b: Snowmelt response to simulated warming across a large elevation gradient, southern Sierra Nevada, California. The Cryosphere 11: 2847–2866.

Naef F, Margreth M. 2017: Niedrigwasser. Auswertung und Messung. Study commissioned by the FOEN (Swiss Federal Office for the Environment). https://www.bafu.admin.ch/dam/bafu/de/dokumente/wasser/externe-studien-berichte/niedrigwasser-auswerrung-und-messung.pdf.download.pdf/Bericht_BAFU_Auswertung_HyBeSt_SoilCom.pdf

Naef F., Margreth M., Floriancic M. 2015: Festlegen von Restwassermengen: Q347, eine entscheidende, aber schwer zu fassende Grösse. Wasser, Energie, Luft 107(4): 277–284.

Najafi M.R., Zwiers F., Gillett N. 2017: Attribution of Observed Streamflow Changes in Key British Columbia Drainage Basins. Geophysical Research Letters 44: 11012–11020.

Nicholls N., Seneviratne S.I. 2015: Comparing IPCC assessments: how do the AR4 and SREX assessments of changes in extremes differ ? Climatic Change 133: 7–21.

Nicolle P., Pushpalatha R., Perrin C., François D., Thiéry D., Mathevet T., Le Lay M., Besson F., Lorraine D. 2014: Benchmarking hydrological models for low-flow simulation and forecasting on French catchments. Hydrology and Earth System Sciences 18: 2829–2857.

OcCC 2000: Workshopbericht «Trockenheit in der Schweiz», Organe Consultatif sur les Changements Climatiques (OcCC). Bern.

Orlowsky B., Seneviratne S.I., 2013: Elusive drought: uncertainty in observed trends and short- and long-term CMIP5 projections. Hydrology and Earth System Sciences 17: 1765–1781.

Painter T.H., Skiles S.M., Deems J.S., Brandt W.T., Dozier J. 2017: Variation in Rising Limb of Colorado River Snowmelt Runoff Hydrograph Controlled by Dust Radiative Forcing in Snow. Geophysical Research Letters 44. https://doi.org/10.1002/2017GL075826

Parajka, J., Blaschke, A.P., Blöschl, G., Haslinger, K., Hepp, G., Laaha, G., Schöner, W., Trautvetter, H., Viglione, A., Zessner, M., 2016: Uncertainty contributions to low-flow projections in Austria. Hydrology and Earth System Sciences 20: 2085–2101.

Pauritsch M., Wagner T., Winkler G., Birk S. 2017: Investigating groundwater flow components in an Alpine relict rock glacier (Austria) using a numerical model. Hydrogeology Journal 25: 371–383.

Pellicciotti F., Bauder A., Parola M. 2010: Effect of glaciers on streamflow trends in the Swiss Alps. Water Resources Research 46: W10522. https://doi.org/10.1029/2009WR009039

Pereira L.S., Keller H.M. 1982a: Recession characterization of small mountain basins, derivation of master recession curves and optimization of recession parameters. IAHS Publ. no 138 243–255.

Pereira L.S., Keller H.M. 1982b: Factors affecting recession parameters and flow components in eleven small Pre-Alp basins. IAHS Publ. no. 138.

Pfannerstill M., Guse B., Fohrer N. 2014: Smart low flow signature metrics for an improved overall performance evaluation of hydrological models. Journal of Hydrology 510: 447–458.

Pfaundler M., Wüthrich T. 2006: Die Saisonalität hydrologischer Extreme. Das zeitliche Auftreten von Hoch- und Niedrigwasser in der Schweiz. Wasser Energie Luft 98: 77–82.

Pfister C., Rutishauser M., 2000: Dürresommer im Schweizer Mittelland seit 1525. Anhang A. In: Trockenheit in Der Schweiz. Workshopbericht. OcCC / ProClim, Bern.

Pfister C., Weingartner R., Luterbacher J. 2006: Hydrological winter droughts over the last 450 years in the Upper Rhine basin: a methodological approach Hydrological winter droughts over the last 450 years in the Upper Rhine basin: a methodological approach. Hydrological Sciences Journal 51: 966–985. https://doi.org/10.1623/hysj.51.5.966

Poff N.L. 2018: Beyond the natural flow regime ? Broadening the hydro-ecological foundation to meet environmental flows challenges in a non-stationary world. Freshwater Biology 63: 1011-1021.

Prudhomme C., Wilby R.L., Crooks S., Kay A.L., Reynard N.S. 2010: Scenario-neutral approach to climate change impact studies: Application to flood risk. Journal of Hydrology 390, 198–209. https://doi.org/10.1016/j.jhydrol.2010.06.043

Pushpalatha R., Perrin C., Le Moine N., Andréassian V. 2012: A review of efficiency criteria suitable for evaluating low-flow simulations. Journal of Hydrology 420–421: 171–182.

Rajczak J., Kotlarski S., Schär C. 2016: Does Quantile Mapping of Simulated Precipitation Correct for Biases in Transition Probabilities and Spell Lengths ? Journal of Climate 29: 1605–1615.

Renard B., Lang M., Bois P., Dupeyrat A., Mestre O., Niel H., Sauquet E., Prudhomme C., Parey S., Paquet E., Neppel L., Gailhard J. 2008. Regional methods for trend detection: Assessing field significance and regional consistency. Water Resources Research 44: W08419.

Rinaudo J., Maton L., Terrason I., Chazot S., Richard-Ferroudji A., Caballero Y. 2013: Combining scenario workshops with modeling to assess future irrigation water demands. Agricultural Water Management 130: 103–112.

Rogger M., Chirico G. B., Hausmann H., Krainer K., Brückl E., Stadler P., Blöschl G.2017: Impact of mountain permafrost on flow path and runoff response in a high alpine catchment M. Water Resources Research 53: 1288–1308. https://doi.org/10.1002/2016WR019341.Received

Rössler O., Addor N., Bernhard L., Figura S., Köplin N., Livingstone D.M., Schädler B., Seibert J. Weingartner R. 2014: Hydrological responses to climate change: river runoff and groundwater. In: Raible C.C., Strassmann K (Eds.): CH-2014 Impacts, toward Quantitative Scenarios of Climate Change Impacts in Switzerland: 57–66.

Safeeq, M., Grant, G.E., Lewis, S.L., Tague, C.L., 2013: Coupling snowpack and groundwater dynamics to interpret historical stream flow trends in the western United States. Hydrological Processes 27: 655–668. https://doi.org/10.1002/hyp.9628

Saft M., Peel M.C., Western A.W., Perraud J., Zhang L. 2016: Bias in streamflow projections due to climate-induced shifts in catchment response. Geophysical Research Letters 43: 1574–1581.

Santos A.C., Portela M.M., Rinaldo A., Schaefli B. 2018: Analytical flow duration curves for summer streamflow in Switzerland. Hydrology and Earth System Sciences 22: 2377–2389.

Sauquet E., Prudhomme C., 2015: A scenario neutral approach to assess low flow sensitivity to climate change. Geophysical Research Abstracts 17: EGU2015-5450–2.

Savenije H.H.G., Hoekstra A.Y., Van Der Zaag P. 2014: Evolving water science in the Anthropocene. Hydrology and Earth System Sciences 18: 319–332. https://doi.org/10.5194/hess-18-319-2014

Sayama T., Mcdonnell J.J., Dhakal A., Sullivan K. 2011: How much water can a watershed store? Hydrological Processes 25: 3899–3908. https://doi.org/10.1002/hyp.8288

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. https://doi.org/10.1016/j.renene.2018.07.104

Scherrer S.C., Christian W., Croci-Maspoli M. 2013: Snow variability in the Swiss Alps 1864–2009. International Journal of Climatology 33: 3162–3173. https://doi.org/10.1002/joc.3653

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.

Schorer M. 1992: Extreme Trockensommer in der Schweiz und ihre Folgen für Natur und Wirt- schaft. Geographica Bernensia G40. Bern.

Schürch M., Kozel R. 2010: Typisierung von Grundwasserregimen in der Schweiz. Konzept und Fallbeispiele. Gas Wasser Abwasser 2010: 955–965.

Seibert J., Vis M.J.P., Lewis E., van Meerveld H.J. 2018: Upper and lower benchmarks in hydrological modelling. Hydrological Processes 32: 1120–1125. https://doi.org/10.1002/hyp.11476

Seibert J., van Meerveld H.J. 2016: Hydrological change modeling: Challenges and opportunities. Hydrological Processes 26: 4966–4971 https://doi.org/10.1002/hyp.10999

Seneviratne S.I., Orth R., Jörg-Hess S., Kruse S., Seidl I., Stähli M., Zappa M., Seibert J., Staudinger M., Stahl K., Weiler M. 2013: Trockenheit in der Schweiz. Aqua Gas 2013: 38–47.

Seneviratne S.I., Nicholls N., Easterling D., Goodess C.M., Kanae S., Kossin J., Luo Y., Marengo J., McInnes K., Rahimi M., Reichstein M., Sorteberg A., Vera C., Zhang X. 2012: Changes in climate extremes and their impacts on the natural physical environment.. In: Field, C.B., Barros, V., Stocke, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen S.K., Tignor M., Midgley P.M. (Eds.): Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC): 109–230. Cambridge University Press, Cambridge / New York.

Seneviratne S.I. 2012: Historical drought trends revisited. Nature 491: 338–339.

Sheffield J., Wood E.F. 2011. Drought. Past problems and future scenarios. Earthscan, London / Washington DC.

Siegrist I., 2015. Die Auswirkungen von Trockenheit im Jahr 2003 im Kanton Solothurn Eine Untersuchung zur Entwicklung lokaler Nutzungskonflikte. Bachelor-Arbeit, Fakultät für Umwelt und Natürliche Ressourcen, Universität Freiburg i.B.

Sivapalan M. 2015. Debates—Perspectives on socio-hydrology: Changing water systems and the '"tyranny of small problems"'—Socio-hydrology. Water Resources Research 51: 4795–4805.

Sivapalan M., Konar M., Srinivasan V., Chhatre A., Wutich A., Scott C.A., Wescoat J.L. 2014. Socio-hydrology: Use-inspired water sustainability science for the Anthropocene. Earth's Future 2: 225–230. https://doi.org/10.1002/2013EF000164.Received

Smakhtin V.U., 2001: Low flow hydrology: a review. Journal of Hydrology 240: 147–186.

Smakhtin V.U., Schipper E.L.F. 2008: Droughts: The impact of semantics and perceptions. Water Policy 10: 131–143. https://doi.org/10.2166/wp.2008.036

Speich M., Bernhard L., Teuling A.J., Zappa M. 2015: Application of bivariate mapping for hydrological classification and analysis of temporal change and scale effects in Switzerland. Journal of Hydrology 523: 804–821. https://doi.org/10.1016/j.jhydrol.2015.01.086

Spreafico M., Weingartner R. 2005: The Hydrology of Switzerland. Selected aspects and results. Reports of the FOWG, Water Series No. 7. Bern.

Stahl K., Kohn I., Böhm M., Freudiger D., Gerlinger K., Seibert J., Weiler M. 2017a: Langfristige Veränderungen der Abflusskomponenten aus Schnee- und Gletscherschmelze in Niedrigwassersituationen am Rhein. Forum für Hydrologie und Wasserbewirtschaftung 38(17): 217–226.

Stahl K., Weiler M., Freudiger D., Kohn I., Seibert J., Vis M.J.P., Gerlinger K., Böhm M. 2017b: The snow and glacier melt components of streamflow of the river Rhine and its tributaries considering the influence of climate change. Final report to the International Commission for the Hydrology of the Rhine Basin (CHR). English version, March 2017.

Stahl K., Weiler M., Kohn I., Freudiger D., Seibert J., Vis M., Gerlinger K. 2016: The snow and glacier melt components of streamflow of the river Rhine and its tributaries considering the influence of climate change – Synthesis report. CHR/KHR report CHR I-25. Lelystad.

Stahl K., Hisdal H., Hannaford J., Tallaksen L.M., van Lanen H.A.J., Sauquet E., Demuth S., 2010: Streamflow trends in Europe: evidence from a dataset of near-natural catchments. Hydrology and Earth System Sciences 14: 2367–2382. https://doi.org/10.5194/hess-14-2367-2010

Stahl K., Hisdal H., Tallaksen L.M. 2008: Trends in low flows and streamflow droughts across Europe. UNESCO Technical report. Paris.

Stahl K., Moore R.D. 2006: Influence of watershed glacier coverage on summer streamflow in British Columbia, Canada. Water Resources Research 42: W06201.

Stahl K. 2001: Hydrological Drought – a Study across Europe. Freiburger Schriften zur Hydrologie 15. Freiburg im Breisgau.

Staudinger M., Seibert J. 2014. Predictability of low flow – An assessment with simulation experiments. Journal of Hydrology 519: 1383–1393. https://doi.org/10.1016/j.jhydrol.2014.08.061

Staudinger M., Stahl K., Seibert J., 2014: A drought index accounting for snow. Water Resources Research 50: 7861–7872. https://doi.org/10.1002/2013WR015143

Staudinger M., Stoelzle M., Cochand F., Seibert J., Weiler M., Hunkeler D. 2019: Your work is my boundary condition! Challenges and approaches for a closer collaboration between hydrologists and hydrogeologists. Journal of Hydrology 571: 235–243.

Staudinger M., Stoelzle M., Cochand F., Wirth S., Carlier C., Seibert J., Weiler M., Stahl K., Brunner P., Hunkeler D., 2018: BAFU - Projekt Niedrigwasser und Grundwasser. Synthesebericht. Study commissioned by the FOEN (Swiss Federal Office for the Environment).

Staudinger M., Stahl K., Stoelzle M., Seeger S., Seibert J., Weiler M. 2017: Catchment water storage variation with elevation. Hydrological Processes 2017: 1–16. https://doi.org/10.1002/hyp.11158

Staudinger M., Weiler M., Seibert J. 2015: Quantifying sensitivity to droughts – an experimental modeling approach. Hydrology and Earth System Sciences 19: 1371–1384.

Stewart I.T. 2009: Changes in snowpack and snowmelt runoff for key mountain regions. Hydrological Processes 23, 78–94. https://doi.org/10.1002/hyp

Stoelzle M., Staudinger M., Weiler M., Stahl K. 2018: Stress testing drought from the bottom up: recharge scenarios to quantify streamflow drought sensitivity. Geophysical Research Abstracts 20: EGU2018-3391. https://doi.org/10.13140/RG.2.2.27856.40969

Stoelzle M., Stahl K., Seibert J. 2015a: Improved baseflow characterization in mountainous catchments. Geophysical Research Abstracts 17: EGU2015-10281.

Stoelzle M., Weiler M., Stahl K., Morhard A., Schuetz T. 2015b: Is there a superior conceptual groundwater model structure for base flow simulation? Hydrological Processes 29: 1301–1313. https://doi.org/10.1002/hyp.10251

Stoelzle M., Stahl K., Morhard A., Weiler M. 2014: Streamflow sensitivity to drought scenarios in catchments with different geology. Geophysical Research Letters 41: 6174–6183.

Stoelzle M., Stahl K., Weiler M. 2013: Are streamflow recession characteristics really characteristic? Hydrology and Earth System Sciences 17: 817–828. https://doi.org/10.5194/hess-17-817-2013

Stucki P., Luterbacher J. 2010: Precipitation, Temperature and Runoff over the Past Few Centuries. Plate 1.4. In: Hydrological Atlas of Switzerland. Federal Office for the Environment (FOEN), Bern.

Tague C.L., Choate J.S., Grant G. 2013: Parameterizing sub-surface drainage with geology to improve modeling streamflow responses to climate in data limited environments. Hydrology and Earth System Sciences 17: 341–354. https://doi.org/10.5194/hess-17-341-2013

Tague C., Grant G.E. 2009: Groundwater dynamics mediate low-flow response to global warming in snow-dominated alpine regions. Water Resources Research 45. https://doi.org/10.1029/2008WR007179

Takayabu I., Kanamaru H., Dairaku K., Benestad R., von Storch H., Christensen J.H. 2016: Reconsidering the Quality and Utility of Downscaling. Journal of the Meteorological Society of Japan. Ser. II 94A: 31–45. https://doi.org/10.2151/jmsj.2015-042

Tallaksen L.M., van Lanen H.A.J. 2004: Hydrological Drought: Processes and Estimation Methods for Streamflow and Groundwater. Developments in Water Science 48. Elsevier, Amsterdam / Oxford.

Tallaksen L.M. 1995: A review of baseflow recession analysis. Journal of Hydrology 165, 349–370.

Teuling A.J., Lehner I., Kirchner J.W., Seneviratne S.I. 2010: Catchments as simple dynamical systems: Experience from a Swiss prealpine catchment. Water Resources Research 46. https://doi.org/10.1029/2009WR008777

Teutschbein C., Seibert J. 2012: Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. Journal of Hydrology 456–457, 12–29. https://doi.org/10.1016/j.jhydrol.2012.05.052

Thomas B.F., Vogel R.M., Famiglietti J.S. 2015: Objective hydrograph baseflow recession analysis. Journal of Hydrology 525: 102–112. https://doi.org/10.1016/j.jhydrol.2015.03.028

Thut W.K., Weingartner R., Schädler B. 2015: Mehrzweckspeicher sichern Wasser- und Energieversorgung. Universität Bern. http://www.nfp61.ch/SiteCollectionDocuments/2016-05_Uni-BE-Mehrzweckspeicher-sichern-Wasser-und-Energieversorgung.pdf.

Thut W.K., Weingartner R., Schädler B. 2016: Zur Bedeutung von Mehrzweckspeichern in der Schweiz. Anpassung an den Klimawandel. Wasser Energie Luft 108: 179–186.

Tian Y., Booij M.J., Xu Y.-P. 2014: Uncertainty in high and low flows due to model structure and parameter errors. Stochastic environmental research and risk assessment 28: 319–332.

van Huijgevoort M.H.J., van Lanen H.A.J., Teuling A.J., Uijlenhoet R. 2014: Identification of changes in hydrological drought characteristics from a multi-GCM driven ensemble constrained by observed discharge. Journal of Hydrology 512: 421–434. https://doi.org/10.1016/j.jhydrol.2014.02.060

Van Loon A.F., Gleeson T., Clark J., Van Dijk A.I.J.M. Stahl, K., Hannaford J., Di Baldassarre, Teuling A.J., Tallaksen L.M., Uijlenhoet R., Hannah D.M., Sheffield J., Svoboda M., Verbeiren B., Wagener T., Rangecroft S., Wanders N., van Lanen H.A.J. 2016a: Drought in the Anthropocene. Nature Geoscience 9: 89–91. https://doi.org/10.1038/ngeo2646

Van Loon A.F., Stahl K., Di Baldassarre G., Clark J., Rangecroft S., Wanders N., Gleeson T., Van Dijk, A.I.J.M., Tallaksen L.M., Hannaford J., Uijlenhoet R., Teuling A.J., Hannah D.M., Sheffield J., Svoboda M., Verbeiren B., Wagener T., van Lanen H.A.J. 2016b: Drought in a human-modified world: Reframing drought definitions, understanding, and analysis approaches. Hydrology and Earth System Sciences 20: 3631–3650. https://doi.org/10.5194/hess-20-3631-2016

Van Loon A.F. 2015: Hydrological drought explained. WIREs Water 2: 359–392.

Vaze J., Post D.A., Chiew F.H.S., Perraud J., Viney N.R., Teng J. 2010: Climate non-stationarity – Validity of calibrated rainfall – runoff models for use in climate change studies. Journal of Hydrology 394: 447–457. https://doi.org/10.1016/j.jhydrol.2010.09.018

Velázquez J.A., Schmid J., Ricard S., Muerth M.J., Gauvin St.-Denis B., Minville M., Chaumont D., Caya D., Ludwig R., Turcotte R. 2013: An ensemble approach to assess hydrological models ’ contribution to uncertainties in the analysis of climate change impact on water. Hydrology and Earth System Sciences 17: 565–578. https://doi.org/10.5194/hess-17-565-2013

Vidal J.-P., Hingray B., Magand C., Sauquet E., Ducharne A. 2016: Hierarchy of climate and hydrological uncertainties in transient low-flow projections. Hydrology and Earth System Sciences 20: 3651–3672. https://doi.org/10.5194/hess-20-3651-2016

Vincent C., Fischer A., Mayer C., Bauder A., Galos S.P., Funk M., Thibert E., Six D., Braun L., Huss M. 2017: Common climatic signal from glaciers in the European Alps over the last 50 years. Geophysical Research Letters 44: 1376–1383. https://doi.org/10.1002/2016GL072094

Viviroli D., Schädler B., Weiler M., Seibert J. 2012: On the risk of obtaining misleading results by pooling streamflow data for trend analyses. Water Resources Management 48: W05601.

Viviroli D., Archer D.R., Buytaert W., Fowler H.J., Greenwood G.B., Hamlet A.F., Huang Y. 2011: Climate change and mountain water resources: overview and recommendations for research, management and policy. Hydrology and Earth System Sciences 15: 471–504.

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 Software 24: 1209–1222. https://doi.org/10.1016/j.envsoft.2009.04.001

von Freyberg J., Allen S.T., Seeger S., Weiler M., Kirchner J.W. 2018: Sensitivity of young water fractions to hydro-climatic forcing and landscape properties across 22 Swiss catchments. Hydrology and Earth System Sciences 22: 3841–3861. https://doi.org/10.5194/hess-2017-720

von Waldow H., Fischer A.M., Kotlarski S., Zubler E., Appenzeller C., Bey I., Bosshard T., Calanca P., Croci-Maspoli M., Fischer E.M., Fuhrer J., Hohmann R., Knutti R., Kull C., Liniger M.A., Lustenberger A., Ritz C., Schär C., Scherrer S.C. 2014: Data basis of CH2014-Impacts – The Swiss Climate Change Scenarios CH2011. In: CH-2014 Impacts, toward Quantitative Scenarios of Climate Change Impacts in Switzerland, 31-40. OCCR, FOEN, MeteoSwiss, C2SM, Agroscope, and ProClim. Bern.

Vormoor K., Rössler O., Bürger G., Bronstert A., Weingartner R. 2017: When timing matters-considering changing temporal structures in runoff response surfaces. Climatic Change 142: 213–226. https://doi.org/10.1007/s10584-017-1940-1

Wagner, T., Pauritsch, M., Winkler, G., 2016: Impact of relict rock glaciers on spring and stream flow of alpine watersheds: Examples of the Niedere Tauern Range, Eastern Alps. Austrian Journal of Earth Sciences 109: 84–98. https://doi.org/10.17738/ajes.2016.0006

Wang, J., Horne, A., Nathan, R., Peel, M., Neave, I., 2018: Vulnerability of Ecological Condition to the Sequencing of Wet and Dry Spells Prior to and during the Murray-Darling Basin Millennium Drought. Journal of Water Resources Planning and Management 144.8: 04018049.

Wehren B., Schädler B., Weingartner R. 2010: Human Interventions. In: Bundi U. (Ed.): The Handbook of Environmental Chemistry 6: 71–92. Springer, Berlin / Heidelberg.

Wehse H., Chaix O., Gander Y., Birrer A., Fritsch M., Meylan B., Zahner S. 2017: Erarbeitung von Massnahmen zur langfristigen Sicherstellung der Wasserressourcen Ein Vorgehen gestützt auf bestehende Planungsinstrumente. Bericht Nr. 7043.18-BP004h. Hunziker Betatech AG Bern / INTEGRALIA AG Bern / emac AG Zürich / Benjamin Meylan Grundw.

Weiler M., Seibert J., Stahl K. 2018: Magic components—why quantifying rain, snowmelt, and icemelt in river discharge is not easy. Hydrological Processes 32: 160–166.

Weingartner R. 2017: Low Water in Switzerland. On different Spatial and Temporal Scales. Oral presentation. CHR Symposium “Low flows in the Rhine catchment” 22–23 Sep 2017, Basel.

Weingartner R., Reynard E., Graefe O., Herweg K., Homewood C., Kauzlaric M., Liniger H., Rey E., Schneider F. 2014: MontanAqua: Wasserbewirtschaftung in Zeiten von Knappheit und globalem Wandel – Wasserbewirtschaftungsoptionen für die Region Crans-Montana-Sierre im Wallis. Forschungsbericht des Nationalen Forschungsprogramms NFP 61. Bern.

Weingartner R., Pfister C. 2007: Wie außerordentlich was das Niedrigwasser im Winter 2005/2006 – Eine hydrologisch-historische Betrachtung des Rheinabflusses in Basel (To what extent was the hydrological winter drought 2005/06 exceptional? – A hydrological-historical review of streamflow. Hydrologie und Wasserbewirtschaftung 51, 22–26.

Wetter O. 2017: The potential of historical hydrology in Switzerland. Hydrology and Earth System Sciences 21: 5781–5803.

Wetter O., Pfister C., Werner J.P., Zorita E., Wagner S., Seneviratne S.I., Herget J., Grünewald U., Luterbacher, J., Alcoforado, M., Barriendos, M., Bieber, U., Brázdil, R., Burmeister, K.H., Camenisch, C., Contino, A., Dobrovolný, P., Glaser, R., Himmelsbach, I., Kiss, A., Labbé, T., Limanówka, D., Litzenburger, L., Nordl, Ø., Pribyl, K., Retsö, D., Riemann, D., Rohr, C., Siegfried, W., Söderberg, J., 2014: The year-long unprecedented European heat and drought of 1540 – a worst case. Climatic Change 125: 349–363. https://doi.org/10.1007/s10584-014-1184-2

Whitfield P.H., Burn D.H., Hannaford J., Higgins H., Hodgkins A., Marsh T., Looser U. 2012: Reference hydrologic networks I . The status and potential future directions of national reference hydrologic networks for detecting trends Reference hydrologic networks I. The status and potential future directions of national reference hydrologic networks. Hydrological Sciences Journal 57: 1562–1579. https://doi.org/10.1080/02626667.2012.728706

Wilby R.L., Dessai S. 2010: Robust adaptation to climate change. Weather 65: 180–185.

Wilby R.L., Harris I. 2006: A framework for assessing uncertainties in climate change impacts: Low-flow scenarios for the River Thames, UK. Water Resources Research 42: W02419.

Wilhite D.A., Glantz M.H. 1985: Understanding : the Drought Phenomenon: The Role of Definitions. Water International 10: 37–41. https://doi.org/10.1080/02508068508686328

Willems P., Mora D., Vansteenkiste T., Taye M.T., Van Steenbergen N. 2014: Parsimonious rainfall-runoff model construction supported by time series processing and validation of hydrological extremes – Part 2 : Intercomparison of models and calibration approaches. Journal of Hydrology 510: 591–609. https://doi.org/10.1016/j.jhydrol.2014.01.028

Wittenberg H., 1999: Baseflow recession and recharge as nonlinear storage processes. Hydrological Processes 13: 715–726.

Woodhouse C.A., Pederson G.T. 2018: Investigating Runoff Efficiency in Upper Colorado River Streamflow Over Past Centuries. Water Resources Research 54. https://doi.org/10.1002/2017WR021663

Yevjevich V. 1967: An objective approach to definitions and investigations of continental hydrologic droughts. Hydrology papers 23. Colorado State University, Fort Collins.

Zahner S. 2017: Haushälterischer Umgang mit Wasserressourcen. Aqua Gas 6: 2–10.

Zappa M., Vitvar T., Rücker A., Melikadze G., Bernhard L., David V., Jans-Singh M., Zhukova N., Sanda M. 2015: A Tri-National program for estimating the link between snow resources and hydrological droughts A Tri-National program for estimating the link between snow resources and hydrological droughts. Proc. IAHS 369: 25–30. https://doi.org/10.5194/piahs-369-25-2015

Zappa M., Bernhard L., Fundel F., Jörg-Hess S. 2012: Vorhersage und Szenarien von Schnee- und Wasserressourcen im Alpenraum. Forum für Wissen 2012: 19–27.

Zappa M., Kan C. 2007: Extreme heat and runoff extremes in the Swiss Alps. Natural Hazards and Earth System Sciences 7: 375–389.

Zwiers F.W., Alexander L.V, Hegerl G.C., Knutson T.R., Kossin J.P., Naveau P., Nicholls N., Schär C., Seneviratne S.I., Zhang X. 2013: Climate Extremes: Challenges in Estimating and Understanding Recent Changes in the Frequency and Intensity of Extreme Climate and Weather Events. In: Asrar G.R., Hurrell J.W. (Eds.): Climate Science for Serving Society: 339–389. Springer, Dordrecht.

Low flow indices referred to in the text

Q_{95}	Flow exceeded in 95% of all observations, corresponding to the 0.05 quantile of the long-term flow duration curve (5% lowest flows).
Q_{347}	Swiss term/abbreviation for the Q_{95} (flow exceeded on 347 days of the year) based on the long-term flow duration curve. For residual water regulations the legally relevant value according to the Federal Act on the Protection of Waters is the Q_{347} based on the observed streamflow over the last 10 years.
Q_{90}	Flow exceeded in 90% of all observations, corresponding to the 0.1 quantile of the long-term flow duration curve (10% lowest flows)
AM_7	Lowest arithmetic mean of 7 consecutive daily values of the flow in a specific period. Mostly determined per low flow year, sometimes also calculated per summer/winter half years, season, or month. Commonly used low flow index. Long-term mean AM_7 often used as a low flow threshold.
AM_x	Lowest arithmetic mean of x consecutive daily values. Besides 7-day mean flow often e.g. 21 or 30 days are used.
Minimum flow	Minimum flow in a specific period (e.g. a low flow year). In German often abbreviated as NQ.
Mean annual minimum (MNQ)	Mean of the annual minimum flow (calculated based on low flow years, hydrological years, or calendar years). In German often abbreviated as MNQ.
0.05, 0.1, .., 0.9 quantile	Quantiles of the flow duration curve. In this report based on the frequency of non-exceedance, i.e. 0.05 quantile: flow non-exceeded in 5% of the cases, 0.9 quantile: flow non-exceeded in 90% of the cases