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Key Points:

- A model framework for the Rhine basin was developed to simulate streamflow during extreme past drought years in future conditions
- Extreme low flows as in 1976, 2003, and 2018 would aggravate in a future with declined glacier cover and snow pack
- Repeating the drought and heatwave of 2003 in the future results in largest reductions in summer streamflow (70% upstream, 30% downstream)

Supporting Information:

Supporting Information may be found in the online version of this article.

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Melting Alpine Water Towers Aggravate Downstream Low Flows: A Stress-Test Storyline Approach

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Abstract Droughts can lead to extreme low flow situations in rivers, with resulting severe impacts. Upstream snow and ice melt in many of the world's mountain water towers can alleviate the hydrological consequences of drought, yet global warming threatens the cryosphere. To improve the understanding of melt water contributions during drought in the case of future glacier retreat, we developed stress-test storyline scenarios to model streamflow and tested them in the European river Rhine basin. Meteorological conditions of past drought and low flow years in Europe, 1976, 2003, and 2018, were repeated at three future moments in time, representing nowadays, near future and far future conditions. The latter two conditions were obtained by climate projections under the RCP8.5 scenario. Results show that the low flow situations caused by the meteorological drought situations aggravate in future conditions, more so for the far future and for the year 2003 because of the relatively large glacier ice melt contribution in the past. Summer (July–September) streamflow may decline by 5%–25% far downstream and 30%–70% upstream and the duration of extreme low flow situations may double compared to the selected past drought events. These results are relevant for the Rhine as a major European river but stand exemplary for many other river basins and highlight the importance of cryospheric changes for downstream low flow situations in a changing climate. The stress-test scenarios allow a glimpse into future extreme low flow events aiding adaptation planning, and might be adapted to include other important low flow drivers.

Plain Language Summary Extended periods with strongly reduced rainfall, in combination with hot summers, lead to accumulating water shortages. As a result, water levels in rivers drop which causes problems, e.g., for shipping, cooling of power plants and drinking and irrigation water supply. During such drought periods, melt water from snow and ice is important for water supply. However, glaciers are projected to further decline in a warming climate, possibly worsen future low flow situations. To quantify this effect, we modeled the amount of water flowing through the Rhine basin (a) for past low flow events in 1976, 2003, and 2018 and (b) for hypothetical situations where we repeat the weather data of those past low flow years at three moments in the future. The results show that flows upstream and downstream in the river Rhine would get even lower in future conditions and cause low flow situations to lengthen considerably. Especially for the year 2003, which had high ice melt contributions in the past, changes are large. In summer, the flow during already critical low flow situations may decrease by up to 70% upstream, and by up to 30% downstream. The results show a glimpse into future low flow events and may help adaptation planning.

1. Introduction

Extreme low flow situations, caused by meteorological droughts and heatwaves and their consequent development into hydrological droughts, lead to a range of negative impacts (e.g., Mosley, 2015; Stahl, Kohn, et al., 2016; Van Slobbe et al., 2016; Wan et al., 2021; Yevenes et al., 2018). During such extreme drought situations, melt water from snow and glaciers in the alpine parts of a basin, also called mountain water towers (Immerzeel et al., 2020; Viviroli & Weingartner, 2004), sustains streamflow in the upstream parts and in the streams and rivers flowing further downstream. During (late) summer drought, other runoff generating processes, such as snowmelt or rainfall, are absent or reduced and this causes the relative contribution of glacier melt water to streamflow to increase, thus amplifying its importance, even far downstream (Ayala et al., 2020; Huss, 2011;

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Kaser et al., 2010; Pritchard, 2019; Stahl, Weiler, et al., 2016). In addition, when drought situations co-occur with heatwaves, glaciers supply extra melt water that can partly compensate for the lack of precipitation (Pelto et al., 2022; Van Tiel et al., 2021; Zappa & Kan, 2007). During past drought events in western Europe (e.g., in 1976 and 2003), upstream melt in, e.g., the river Rhine basin, could sustain streamflow further downstream, but despite the melt water contributions, these extreme drought events still led to restrictions on water use, impairment of shipping, problems with power plant cooling systems and a deterioration of water quality (e.g., Jonkeren et al., 2007; Massarutto et al., 2013; Vinke et al., 2022).

However, these important melt water contributions during drought situations are under threat due to ongoing and future climate warming. The reduction in melt water supply may worsen critical low flow situations in basins around the world. Climate warming is affecting the cryosphere, with less precipitation falling as snow, earlier start of the snowmelt season and retreating glaciers due to (strong) negative glacier mass balances (e.g., Huss et al., 2017; Nepal, 2016; Nie et al., 2021; Schmucki et al., 2015; Sommer et al., 2020). For the European Alps, Zekollari et al. (2019) showed that glacier volume is expected to reduce by around 50% in 2050 compared to the ice volume in 2017 and by 2/3 to complete disappearance by the end of the 21st century, depending on the future emission scenario. At the same time, the frequency and intensity of extreme meteorological conditions such as droughts and heatwaves are projected to increase in a warming climate (e.g., Beniston et al., 2007; Gobiet et al., 2014; Kundzewicz et al., 2006; Van der Wiel et al., 2021) and current extremes are sometimes presented as a precursor of future events (e.g., Beniston, 2004; Samaniego et al., 2018). How these two processes, future retreating glaciers and extreme droughts, will affect downstream low flows and related water use restrictions in large river basins has not yet been adequately quantified.

The typical model chain used for hydrological climate change impact assessments is forcing a hydrological model with an ensemble of climate model projections and comparing past and future simulations of streamflow. For example, Lutz et al. (2014) used this approach for river basins in High Mountain Asia, Schnorbus et al. (2014) for catchments in British Columbia and Feyen and Dankers (2009) for Europe, with a special focus on low flows. Due to the large spread in future climate projections and the many intertwined hydrological processes taking place, changes in certain streamflow characteristics, e.g., hydrological regime or low and high flow statistics, are commonly analyzed with large uncertainties (Addor et al., 2014; Marx et al., 2017). There has been less attention on analyzing (a) the detailed hydrological processes and (b) specific water use restrictions of future extreme events. This may in part be due to the nature of climate model projections that are statistical representations of future climates. The order of warm and cold and wet and dry years can vary greatly between different climate models that represent the same future climatic conditions. Extreme years may therefore occur at various moments in the future in different climate model simulations. This may be problematic for analyzing hydrological systems that change over time, such as glacier-fed basins under climate change. The timing of an extreme meteorological event is namely key, because the hydrological system state (e.g., level of glacier retreat) can considerably determine the hydrological response.

Few studies focused on changing streamflow in large glacier-fed river basins and on the role of glaciers during drought in these basins. Pritchard (2019), e.g., calculated the amount of melt water released by glaciers in High Mountain Asia during an average and during a drought year and compared it with precipitation estimates to derive melt fractions for a large set of upstream glacierized dam catchments. The study shows that fractions increase during drought, mainly due to the large decreases in precipitation input rather than increased melt. However, the study did not look at streamflow and as a result did not look at how melt water inputs affected streamflow further downstream. Biemans et al. (2019) simulated the contribution of snow and glacier melt to discharge and irrigation in the Asian basins of the Indus, Ganges, and Brahmaputra, thus coupling upstream flow to downstream water demand. However, the study did not look at drought years in particular. In general, most basin scale glacio-hydrological studies focus either on the upstream parts of a basin, or even solely the glaciers, and provide only a rough estimation of the downstream hydrological impacts of changing flows and melt water contributions (e.g., Comeau et al., 2009; Huss, 2011; Huss & Hock, 2018; Junghans et al., 2011), or they focus on the whole basin but with uncertainties for the upstream alpine parts because of a too coarse resolution and absence of a specific glacier melt and retreat module (e.g., Buitink et al., 2021; Rottler et al., 2021; Shrestha et al., 2012).

For usable predictions, there is a need to apply a modeling framework that includes both the complex alpine parts and the downstream parts of large river basins to assess how streamflow is affected by drought and a changing cryosphere. We suggest to use so called event-based story line scenarios (Shepherd et al., 2018; Sillmann et al., 2021), as a complement to climate model projections, to analyze how known past events are influenced by future cryospheric and basin conditions. This approach overcomes the problem of random timing of future extreme drought events in climate projections. Such alternative modeling scenarios have been used in other contexts and studies, all aiming for (a) a better understanding of process changes and (b) system response related to practice and management during extreme conditions. Buitink et al. (2021), e.g., swapped the model forcing between two different decades, i.e., temperature, precipitation, and evaporation, each in a separate hydrological model run, to disentangle their effects on streamflow changes in the Rhine basin. Stoelzle et al. (2020) and Hellwig et al. (2021) introduced a "stress-test" approach, in which past drought events were modeled and altered by reducing the groundwater recharge before the event for German catchments. They aimed to test the sensitivity of the groundwater system to address relevant questions for water management, namely, "could the event have been even worse?" In the context of changing glacier melt contribution, Koboltschnig et al. (2007) asked the question, "what if the climatically extreme summer of 2003 had happened in 1979?" and applied it as a stress-test storyline. They modeled the extreme summer of 2003 with both the glacier outline of 2003 and the larger one from 1979, for an Austrian headwater catchment and found streamflow amounts would have been up to 12% higher in July and August if the 2003 meteorological conditions had happened in earlier years. "Stress-test storylines," here defined as model scenarios in which extreme events (stresses) from the past are used or are worsened ("stressed"), provide complementary scenarios to general climate scenarios to increase our insights into the sensitivity of the studied hydrological system and its water management.

To analyze the effect of a changing cryosphere on summer flows and downstream low flows during drought in a large river basin, we apply such a stress-test storyline model approach and take the major transboundary European river Rhine basin as an example. As a transboundary organization, the International Commission for the Hydrology of Rhine basin raised interest in these changes and this study builds on models and data of a project to support adaptation planning (Stahl et al., 2022). Here, we focus on the "what-if" question "what will happen if meteorological conditions similar to a past observed low flow situation were to occur again in the future?" We develop a modeling framework to simulate streamflow and its components ice, snow, and rain for the glacierized headwaters and the rest of the Rhine basin. We select three extreme drought years that have occurred in the past, 1976, 2003, and 2018, and compare the streamflow simulations of these original extreme years with the years repeated in different future conditions when glaciers have further retreated and quantify the changes in streamflow. To add value to those model predictions and create directly usable storylines, we also apply critical water use restriction thresholds. These thresholds concern environmental flows, hydropower generation, river navigation, and drought warning levels.

2. Study Area

The Rhine basin was chosen here as a large river basin that originates in a glacierized mountain area, to study the effect of changed glacier and basin conditions on streamflow during extreme past droughts. The river Rhine is one of Europe's major rivers and is of high economic, ecological, and societal importance. It originates in the European Alps in Switzerland and flows through Germany to the Netherlands, with tributaries in France, Austria, Belgium, and Luxembourg (Figure 1). The Rhine basin upstream of Lobith (border between Netherlands and Germany) covers 159,896 km^2. In 1973, the total glacierized area in the Rhine basin was around 400 km^2, and covered 0.27% of the basin. The glacier area has been decreasing since then, with 0.21% coverage in 2003 and 0.18% in 2010 (based on data by: Fischer et al. (2014), Müller et al. (1977), Maisch (2000), and Paul et al. (2011)).

To simulate streamflow and its components snow (Q_{snow}), ice (Q_{ice}), and rain (Q_{rain}), the Rhine basin was subdivided into two parts: the glacierized headwaters upstream of the highest gauging stations or first major confluence and the rest of the basin (Figure 1). The glacierized headwaters of the Rhine basin ($n = 66$), delineated by Freudiger et al. (2020), cover 3% of the Rhine basin upstream of Lobith and vary in size from 10 to 230 km^2 and have a glacier cover ranging from almost 0% to 38% (Figure 1). Important gauges along the Rhine are the gauge at Basel, that integrates the flow in the upper basin, including the Alps (Hänggi & Weingartner, 2011; Pfister et al., 2006), the gauge at Kaub, that is located at one of the narrowest stretches and thus represents a critical threshold for shipping (Jonkeren et al., 2011), and the gauge at Lobith, that measures all the water that enters the Netherlands and is therefore a critical indicator for drought management plans in the Netherlands (De Vries et al., 2021).

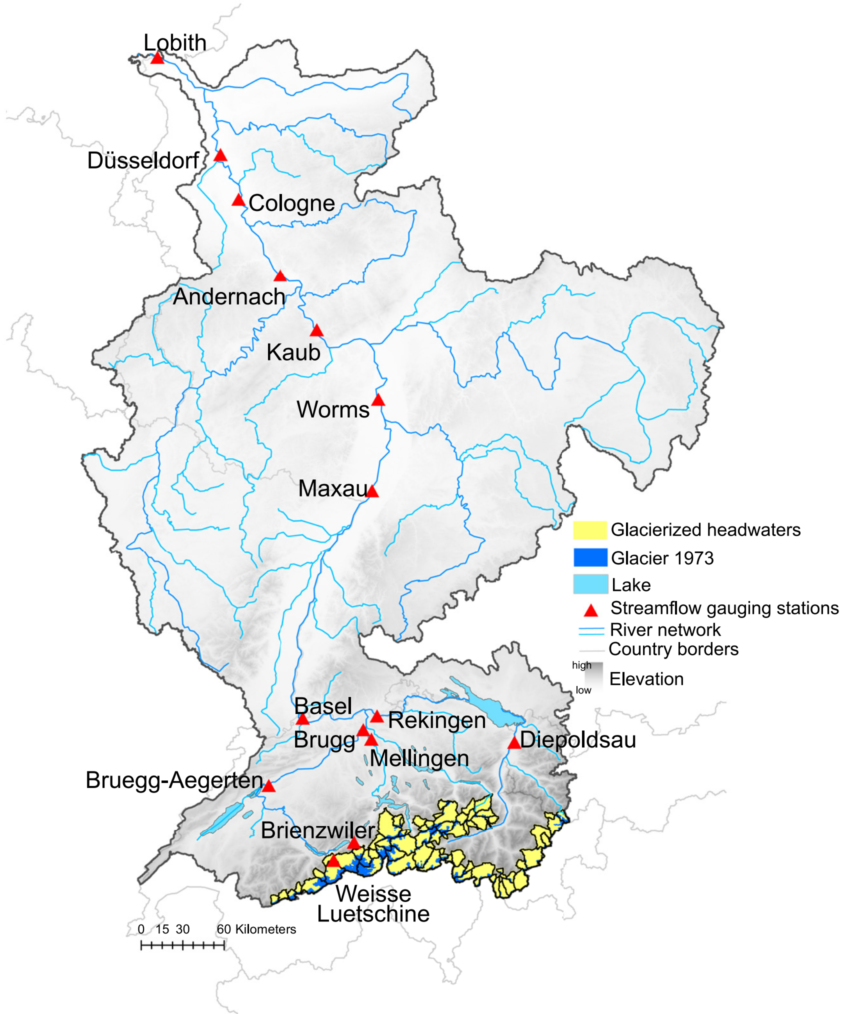

Figure 1. Map of the Rhine basin. The gauges that were used in this study are indicated.

The hydrological regime along the Rhine changes from upstream to downstream. In the upstream parts, flows are high from May to September, due to the melt of snow and ice, and very low during winter when precipitation falls as snow. This pattern continues downstream, but with an earlier timing of the annual peak flow and higher flow during winter. Downstream of Basel, the regime changes with highest flows in winter, and lowest flows in September/October. The precipitation regime also differs within the basin. In most of the basin, summer receives the highest amount of precipitation, but in the eastern part of the basin and downstream of Lobith, in the Netherlands, autumn and winter are wettest. The driest season is spring in the downstream half of the basin, and mostly winter in the upstream half of the basin. Differences in precipitation amounts between the wettest and driest season are higher (>200 mm) in the higher elevated regions of the basin.

3. Methods and Data

3.1. Hydrological Modeling

Daily streamflow and its components Q_{ice}, Q_{snow}, and Q_{rain} for the Rhine basin were modeled using two linked hydrological models, similar as in Stahl, Weiler, et al. (2016) and Stahl et al. (2022). We used a modeling framework to simulate future basin conditions, to apply the stress-test scenarios and to analyze process changes by looking at the different streamflow components.

For the glacierized headwater catchments, the HBV-light model was used (Seibert & Vis, 2012; Seibert et al., 2018). HBV-light has been used in many other studies to simulate streamflow of alpine catchments (e.g., Alvarez-Garreton et al., 2021; Finger et al., 2015; Girons Lopez et al., 2020; Konz & Seibert, 2010; Van Tiel et al., 2018). It is a semidistributed model using elevation (in this study at intervals of 100 m and for the glacier 10 m) and aspect classes (three classes) and it includes the delta-h parametrization to simulate glacier retreat (Huss et al., 2010; Seibert et al., 2018) and a snow redistribution module, essential in high elevation catchments (Freudiger et al., 2017). The simulated streamflow and its components at the outlet of the headwater catchments were used as lateral inflow to the river network of the hydrological water balance model LARSIM (Large Area Runoff Simulation Model; Ludwig & Bremicker, 2006). The distributed LARSIM model was used to simulate the other tributaries in the Rhine basin and to route the headwater streamflow through the basin. The LARSIM model was used at 1 × 1-km resolution upstream of Basel (LARSIM-CH), and 5 × 5-km downstream of Basel (LARSIM-ME). The model setup of LARSIM-CH consists of four models and was provided by the "Landesanstalt für Umwelt Baden-Württemberg" and the "Amt der Vorarlberger Landesregierung." The LARSIM-ME model was provided by the "Bundesanstalt für Gewässerkunde" (Germany).

Snow and ice melt is simulated using a degree day approach, with different melt factors for ice and snow in HBV, a degree day approach in LARSIM-ME and an energy balance method in LARSIM-CH. The models furthermore include interception, evaporation, and soil and groundwater flow routines. Potential evapotranspiration (PET) was estimated based on temperature using Hamon for the headwaters. For the LARSIM part of the modeling, actual evapotranspiration was estimated using Penman-Monteith. Reservoirs present in the upper part of the Rhine basin are represented as four cumulative reservoirs for which operation rules have been estimated in the LARSIM model. To track the different streamflow components (Q_{ice}, Q_{snow}, and Q_{rain}) through the basin, a parallel mixing tank with a small volume is used. This way the effect of ice melt, snowmelt, or rainfall input, passing through the storages, lakes, and reservoirs is simulated, rather than the movement of the particles (for a detailed description see: Stahl et al. (2017) and Weiler et al. (2018)). Note that Q_{snow} includes both snowmelt on and off the glaciers.

The HBV-light model was calibrated for each of the headwater catchments on glacier volume change between 1973 and 2010 from modeled ice thicknesses (Fischer et al., 2014; Huss & Farinotti, 2012; Müller et al., 1977), daily snowline elevation from Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover data (Fugger, 2018; Krajčí et al., 2014), a combination of observed and modeled catchment daily Snow Water Equivalent (SWE) between 1,900 and 2,500 m a.s.l. obtained from SLF (Swiss institute for Snow and Avalanche Research), and also streamflow, if available (15/66 catchments) (Freudiger et al., 2020; Van Tiel et al., 2022b). For the ungauged catchments, a regionalization procedure, using all Swiss gauged glacierized catchments (also in Rhone, Ticino, and Inn basins), determined the rainfall-runoff parameters, while snow and ice related parameters were recalibrated (Freudiger et al., 2020). LARSIM was used with an existing parametrization from earlier applications of the model (Stahl, Weiler, et al., 2016).

Input for the HBV-light model consisted of daily precipitation (P) and temperature (T) data, derived from the MeteoSwiss gridded products RhiresD and TabsD (~2 × 2-km resolution) (MeteoSwiss, 2017, 2019). For LARSIM, the meteorological input, including P, T, radiation, relative humidity, and wind speed, were derived from station data (1,482 stations) and the gridded HYRAS product (Rauthe et al., 2013; Razafimaharo et al., 2020). For the period 2016–2019, a smaller set of stations was used for the interpolation in the LARSIM model due to changes in data availability and gap filling algorithms. To simulate future glacier retreat and streamflow, seven GCM-RCM climate model combinations from the EURO-CORDEX (Jacob et al., 2014) ensemble's RCP8.5 scenario runs (see Figure S4 in Supporting Information S1) were used as model forcing, after a multivariate, including all respective input variables, bias correction had been applied based on the period 1981–2010 (Cannon, 2018; Meyer et al., 2019). The RCP8.5 scenario is used here as a benchmark to derive future conditions and compare the stress-test simulations with. The RCP8.5 scenario, however, only provides one possible future evolution of the climate, and is also called the worst-case scenario (Hausfather & Peters, 2020). We chose only one scenario, since the focus is on understanding the changes rather than attributing them to specific climate scenarios. The RCP8.5 scenario was chosen here as it provides the most pronounced changes and the largest range of future outcomes (i.e., a situation with strong glacier retreat). These are needed to understand the changes in the hydrological mountain river basin system and consequently, identify future risks for water management.

This modeling framework for the Rhine was run in transient mode with Run 1: from October 1973 to 2019, using meteorological observations as input, and with Run 2: from October 1973 to 2100 with the seven GCM-RCM combinations. The starting date of the simulations was determined by the available ice thickness data, needed for initialization of the model. From Run 1, the streamflow signal during the selected drought years was extracted, to serve as a reference for the stress-test runs. From both Run 1 and Run 2, model states were saved to be used as changed initial future conditions for the stress-test modeling (see Section 3.3).

3.2. Selection of Past Drought Years

Three major drought and low flow years within the observation period 1974–2019 were selected for the stress-test model approach, namely 1976, 2003, and 2018. At the downstream gauging stations in the basin (Basel and Lobith), these 3 years had both the lowest observed 7-day minimum flow in summer and lowest total average summer flow within the selected period. The 3 years cover low flow and extreme drought years in different decades. Associated meteorological conditions of these events have been described in detail in other studies (Baker et al., 2021; Bakke et al., 2020; Buras et al., 2020; Hannaford et al., 2011; Rebetez et al., 2006; Van der Wiel et al., 2021).

Although all 3 years experienced a concurrent drought and heatwave, the 2003 and 2018 low flow years were warmer than 1976, especially in late summer (August and September) and the temperatures were exceptional for a longer period (Figure 2). Precipitation in 1976 was far below average from February to June, and in August. Also, the antecedent year, 1975, was characterized by low precipitation amounts in October and December. In 2003 and 2018, precipitation was below average from February to September, and in 2018, precipitation continued to be below average until November. In contrast to the antecedent conditions of 1976, the last months of 2002 and 2017 were relatively wet, especially November 2002.

3.3. Stress-Test Storylines: Past Drought Years in Future Conditions

To "stress-test" how changed future conditions and glacier retreat affect the streamflow response to extreme meteorological conditions, the model input data from the three drought calendar years (1976, 2003, and 2018) were extracted and used as model forcing (drought-scenarios) at three different moments in time (a) nowadays (2018), (b) near future (2031), and (c) far future (2071). For each of them, the model state at the end of the calendar years 2017, 2030, and 2070, respectively, was saved (Table 1). The saved model state included the glacier extent, the snow, soil, and groundwater storages and the lake and reservoir levels. For the near and far future seven model states, from the different climate model combinations of RCP8.5, were saved (Run 2) and all of them were combined with each of the three drought-scenario years. For the drought-scenario 2018, the nowadays run corresponded with the reference run.

In addition to these initial condition stress-tests, we modeled the selected drought years during their original year of occurrence without the glacier melt contribution (no-glacier scenario) (Table 1). For this, several options were tested. Removing the glacier in the headwaters modeling, i.e., assigning the glacier Hydrological Response Units (HRUs) as nonglacierized, resulted in unrealistic high snow packs due to the missing conversion from snow to ice on the glacier surface. Instead, the Q_{ice} component in the headwaters was subtracted from total streamflow from the model output for the headwaters for the no-glacier scenario. For the rest of the Rhine basin, the changed input from the headwaters (i.e., no-glacier scenario) was routed through the Rhine basin using a separate model run. Due to the reduced amounts of water coming from the upstream headwaters in the no-glacier scenario and reservoir operations in the upstream part of the Rhine basin, changes in the other streamflow components Q_{snow} and Q_{rain} amounts can occur, in otherwise exactly similar conditions as the original model runs.

3.4. Changing Drought, Low Flow, and Water Restriction Characteristics

Climate model data characterizes future occurrences of meteorological drought. To put the meteorological conditions of the stress-test year in perspective of these future projections, they were compared with the RCP8.5 climate model ensemble. For each of the selected drought years, characteristic months were selected regarding precipitation (low) and temperature (high). The characteristic months varied per variable and per drought year. The anomaly of the aggregated characteristic months was calculated based on the hindcast period (1974–2019) for the drought years. The anomaly was calculated for the upstream and the downstream meteorological stations. Here, upstream was defined as the hydrological catchment of the Rhine until Basel with a buffer of 30 km surrounding it, and downstream included the other stations. For these analyses, the selection was based on 915

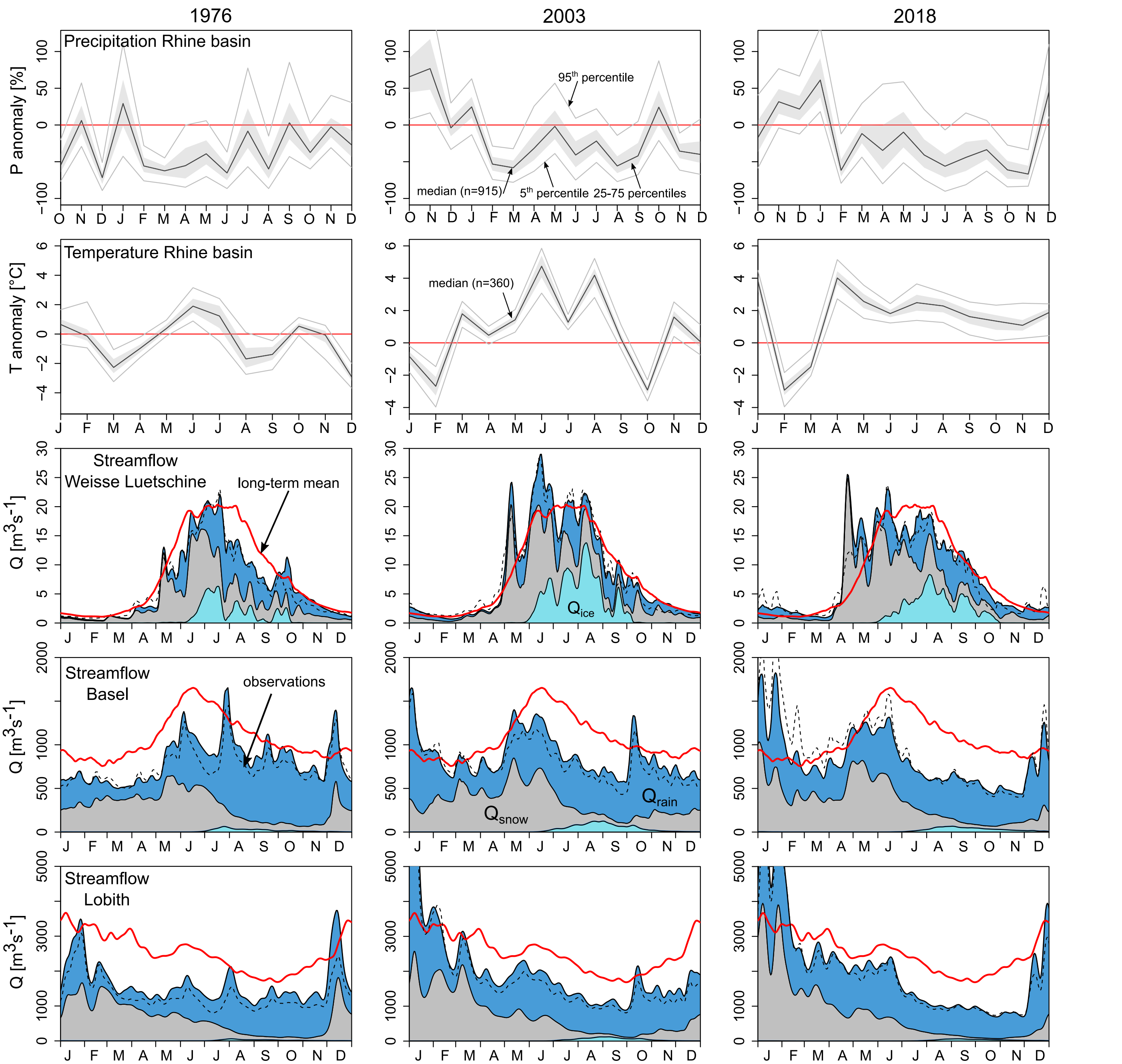

Figure 2. Hydrometeorological conditions of the selected drought and low flow years. The first row shows precipitation anomalies including October-December of the previous calendar year. Temperature anomalies and streamflow are shown for the calendar year. The distribution in the precipitation and temperature anomalies refers to the different meteorological stations in the Rhine basin. Streamflow is smoothed with a 7-day moving window.

precipitation stations and 360 temperature stations that had data throughout the period 1974–2019. The upstream part included 195 precipitation stations and 157 temperature stations and the downstream precipitation and 203 temperature stations. The anomalies were based on the mean of the respective station selections. For the future projections, the anomalies were calculated in a similar way, but using the climate model projections of 1974–2019 as a reference. To stress the importance of timing of future extremes, an 11-year period around the "now," "near future," and "far future" conditions were selected. Thus, past conditions (*P* and *T* anomalies) were compared with future meteorological conditions in an 11-year period around the "now," "near future," and "far future" conditions of the climate model ensemble.

Table 1
Overview of the Model Simulation Details of the Different Stress-Test Scenarios

	Reference	No-glacier	Nowadays	Near future	Far future
Drought-scenario 1976	Hindcast 1976	Hindcast 1976 without Q_{ice}	IC = 31-12-2017 (Run 1) + met = 1976	IC = 31-12-2030 (Run 2) + met = 1976	IC = 31-12-2070 (Run 2) + met = 1976
Drought-scenario 2003	Hindcast 2003	Hindcast 2003 without Q_{ice}	IC = 31-12-2017 (Run 1) + met = 2003	IC = 31-12-2030 (Run 2) + met = 2003	IC = 31-12-2070 (Run 2) + met = 2003
Drought-scenario 2018	Hindcast 2018	Hindcast 2018 without Q_{ice}	*x*	IC = 31-12-2030 (Run 2) + met = 2018	IC = 31-12-2030 (Run 2) + met = 2018

Note. Rows indicate the different drought years and the columns represent the different scenarios that were compared. IC = initial condition and met = meteorological forcing, respectively.

The resulting streamflow projections of the stress-test simulations were compared with the original simulations of the past drought years to infer changes in low flows. Results are mostly shown for the gauging stations Weisse Luetschine, Basel, and Lobith, representing a glacierized headwater catchment, the upstream part of the Rhine basin and the downstream outflow, respectively. For the near and far future conditions, the range of simulations shown is coming from the seven climate model forced initial conditions. These results are either represented as different lines or as bars, with the median indicated with a horizontal line. To investigate how extreme the stress-test streamflow simulations are with respect to the recent past, 7-day moving streamflow percentiles were calculated based on the simulated period 1974–2019 (Run 1). Changes in total summer streamflow (July-September) were compared with the ice melt contribution during summer to analyze how changes in flow are related to a reduction in the Q_{ice} contribution to streamflow. To examine the impact of the stress-tests on streamflow at a weekly resolution, calendar weeks with the highest relative ice melt contribution were selected, for each drought year and for each gauging station. This week was then compared with the same calendar week in the stress-test simulations and changes in the three streamflow components were examined.

Four drought and water use thresholds were calculated to analyze how the changed flow conditions in the stress-test simulations affect drought impacts. For the upstream station Bruegg-Aegerten along the Aare, the Q_{347}, or the 95th percentile of the daily streamflow for a reference period, in our study 1980–2010, was calculated. This metric is used in Switzerland to determine minimal flow requirements (Kohn et al., 2019). Bruegg-Aegerten has a flow regime with lowest flows in February and March and the value calculated for the reference period mostly refers to this period. Q_{347} is calculated for the hindcast (Run 1) and for the seven members of the climate model projections. Subsequently, the days with flow lower than Q_{347} are counted per calendar year. The same procedure is done for the various stress-test years. For Basel, the water availability for hydropower production at the Kemps power plant was estimated. For this, the flow above monthly varying minimum flow requirements (52–180 m^3/s) and flow needed for the fish pass (8 m^3/s) and below the maximum flow limit (1,400 m^3/s), was calculated and summed for each calendar year. For Kaub, the days per year that the flow is above the high (3,445 m^3/s) or low flow (784 m^3/s) shipping thresholds were calculated (GIQ, 2014). For Lobith, the days with drought alert level 1 were calculated. The Rhine flow at Lobith into the Netherlands provides an important water supply and low flows in the Rhine are part of the warning system to alert for drought conditions (De Vries et al., 2021). The threshold for the Rhine varies from 1,000 m^3/s in winter and spring, to 1,400 m^3/s for May, 1,300 m^3/s for June, 1,200 m^3/s for July, and 1,100 m^3/s for August.

4. Results

4.1. Characteristics of Past Low Flow Years

The different dynamics of the cumulative precipitation deficits and heatwaves in the three drought years resulted in different streamflow responses (Figure 2). In general, the streamflow simulations match the observations during these extreme years well. For 1976 and 2003, the simulations and observations have the same dynamics, but the simulations have a slight positive bias at Basel and Lobith. In 2018, the streamflow simulations are underestimated in the first half year at Basel, but closely follow the observations during the rest of the year and at Weisse Luetschine and Lobith (Figure 2).

In 1976, streamflow in the downstream reaches of the Rhine basin was low throughout the year, in particular from February until the beginning of July. In Lobith (basin outlet), the lowest flow was recorded on July 11 in 1976.

In the model simulations (Run 1), the lowest flow occurred on September 1, which resembles a second minimum flow day also in the observations. According to the model simulations, the snowmelt contribution was average to low, especially in May and June. The ice melt contribution in 1976 was shifted to approximately 1 month earlier compared to the long-term mean and was the lowest compared to the other two drought years. Maximum simulated daily ice melt contributions in 1976 were 39.4%, 5.6%, and 3.2%, at Weisse Luetschine, Basel, and Lobith, respectively.

In 2003, in contrast, the ice melt contribution was much higher than the long-term average, throughout the summer. As a result, the summer streamflow anomalies were positive in 2003 for the upstream gauging station Brienzwiler and for the headwaters that had a relative glacier cover larger than 8%. Flows in 2003 were relatively high between April and June in the headwaters and in the upstream part of the Rhine basin at Basel because of the high snowmelt contribution. Flows were extremely low from July to September at the gauges Basel and Lobith (Figure 2). The lowest flow in Lobith was recorded on September 28 (September 27 in the simulations). Maximum simulated daily ice melt contributions in 2003 were 63.7%, 18.6%, and 12.1%, at Weisse Luetschine, Basel, and Lobith, respectively.

In 2018, the flows in July, August, October, and November at Basel and Lobith were the lowest within the observed study period 1974–2019. In 2018, flows were closer to average conditions until the mid of June, partly due to the above-average snowmelt contribution. Compared to 2003, the low flow situation prolonged beyond September, resulting in the day of lowest flow occurring later in autumn (1 December/25 October at Basel, for observations and simulations, respectively and 29 October/28 October at Lobith. The difference between observations and simulations is also here caused by two low flow minima per year). Maximum daily simulated ice melt contributions in 2018 were 47.8%, 10.9%, and 6.4%, at Weisse Luetschine, Basel, and Lobith, respectively.

4.2. Future Cryospheric and Meteorological Conditions

The simulations forced by the ensemble of future climate scenarios under the RCP8.5 scenario (Run 2) show strong glacier retreat in the Rhine basin and its subcatchments (Figure 3). Compared to the start of the simulations in 1973, the glacier area in the whole Rhine basin has diminished by 36% in 2018. By 2030 and 2070, the glacier area is projected to have declined by 39%–51% and 85%–96%, respectively. The rate of glacier retreat varies between catchments and regions. For some catchments, substantial changes in glacier area are simulated between 1976 and 2003, but for other catchments glaciers retreated more strongly after 2003. Comparing the hindcast simulation, from which the "nowadays" conditions are extracted, with the ensemble of climate projections, from which "near" and "far future" conditions are taken, shows that the hindcast simulation is at the lower end of the climate model ensemble. This may result in a higher glacier cover in some of the "near future" conditions when comparing them with the 2018 year and "now" conditions. For the "far future" conditions, glaciers have strongly retreated and cover an area less than 60 km^2 in the Rhine basin.

Past extreme drought years have been suggested to be a precursor of future events that may occur more regularly (e.g., Beniston, 2004; Samaniego et al., 2018). To put the stress-test results into perspective, we compared some of the meteorological characteristics of the past drought years with meteorological conditions in the future climate model ensemble (Figure 4). In general, this comparison shows that future extreme drought events are not necessarily much drier, but they are much warmer in the RCP8.5 ensemble, especially for the upstream part of the Rhine basin. Looking at the distributions of future combined precipitation and temperature anomalies, the past selected drought years seem still plausible in a future climate, despite the strong warming trend. However, the results shown here may indicate that not all climate scenarios may potentially capture extreme meteorological drought events (strong P deficits), especially in the downstream parts of the Rhine basin. Overall, the results suggest that meteorological conditions similar to past drought years will occur more frequently under the RCP8.5 scenario.

4.3. Streamflow and Low Flows During Past Drought Years in Future Basin Conditions

If the meteorological conditions of past low flows were to occur again in the future when glaciers will have progressively retreated, low flows aggravate (Figure 5). The relative changes in streamflow between the original drought years and the stress-tested drought-scenario years are larger for the upstream headwater catchment Weisse Luetschine catchment (13.5% glacier cover in 2010), in which glacier and snowmelt contributions have a relatively larger share in total streamflow, compared to the downstream stations Basel and Lobith.

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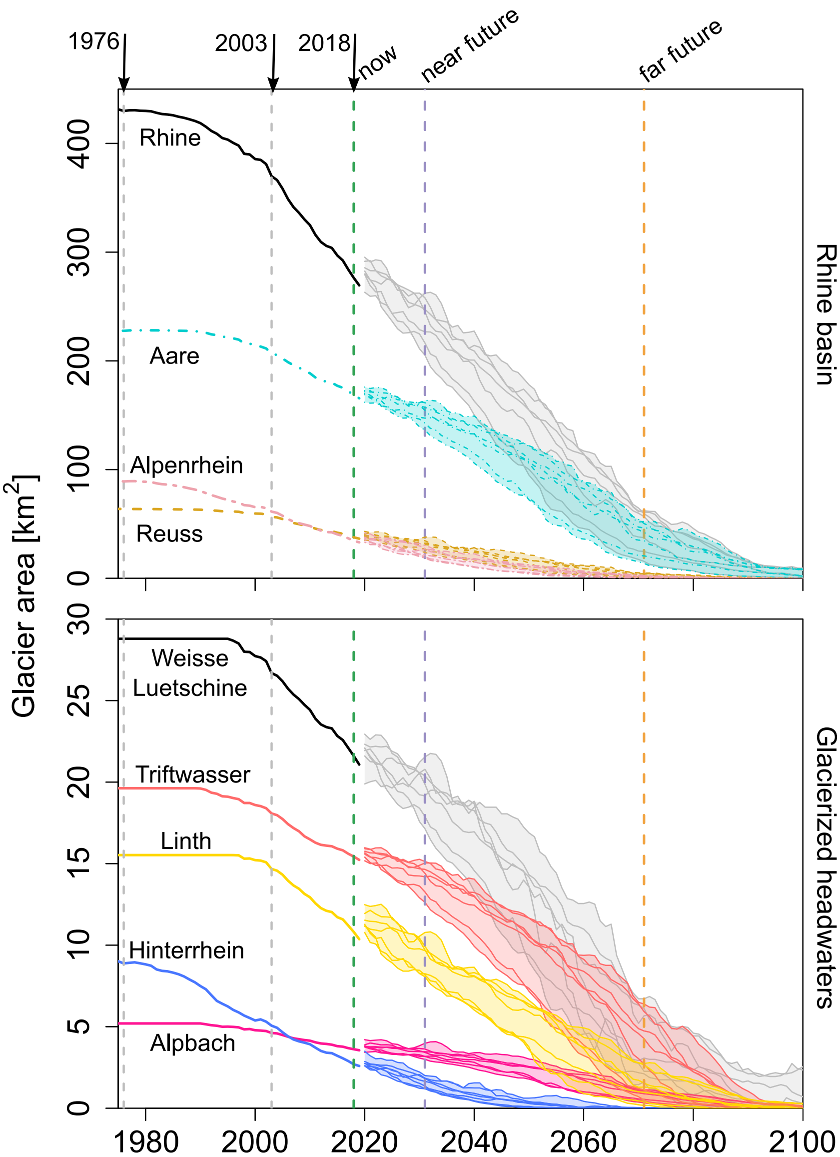

Figure 3. Glacier area evolution in the Rhine basin, its subbasins and in the glacierized headwaters. From 1976 to 2019, the hindcast simulations are shown and from 2020 to 2100, the ensemble of climate model projections of RCP8.5 are shown.

Furthermore, the stress-test effect depends on the drought year. In comparison to 1976 and 2018, the drought-scenario year 2003 shows the largest changes relative to the original low flow year. This can be attributed to the larger ice melt contribution in 2003 because of the exceptionally high temperatures, especially in August, when glacier melt usually peaks (Figure 2). This ice melt component is greatly reduced in the different future conditions stress-tests, due to glacier retreat. The stress-test results show that in the future, flows under drought-scenario 2003 may become extremely low and even out of range of the current lowest flow situations (Figure 5). For drought-scenario years 1976 and 2018, the relative changes in the stress-test scenarios are smaller but are evident around end of June/beginning of July for 1976 and in August for 2018.

The changes in streamflow in the stress-test simulations compared to the reference drought years are larger in the far future conditions compared to the nowadays situation. Nonetheless, according to the simulations, the effect of retreated glaciers would already have been noticeable if the meteorological conditions of 2003 had happened again around the year 2018 (nowadays). For the drought-scenario year 1976 repeated in nowadays conditions, the simulated flow is relatively higher compared to the reference year, for Basel and Lobith (Figure 5). This increase relates to a higher snowmelt component, because the snow pack at the end of 1975 (year preceding the original

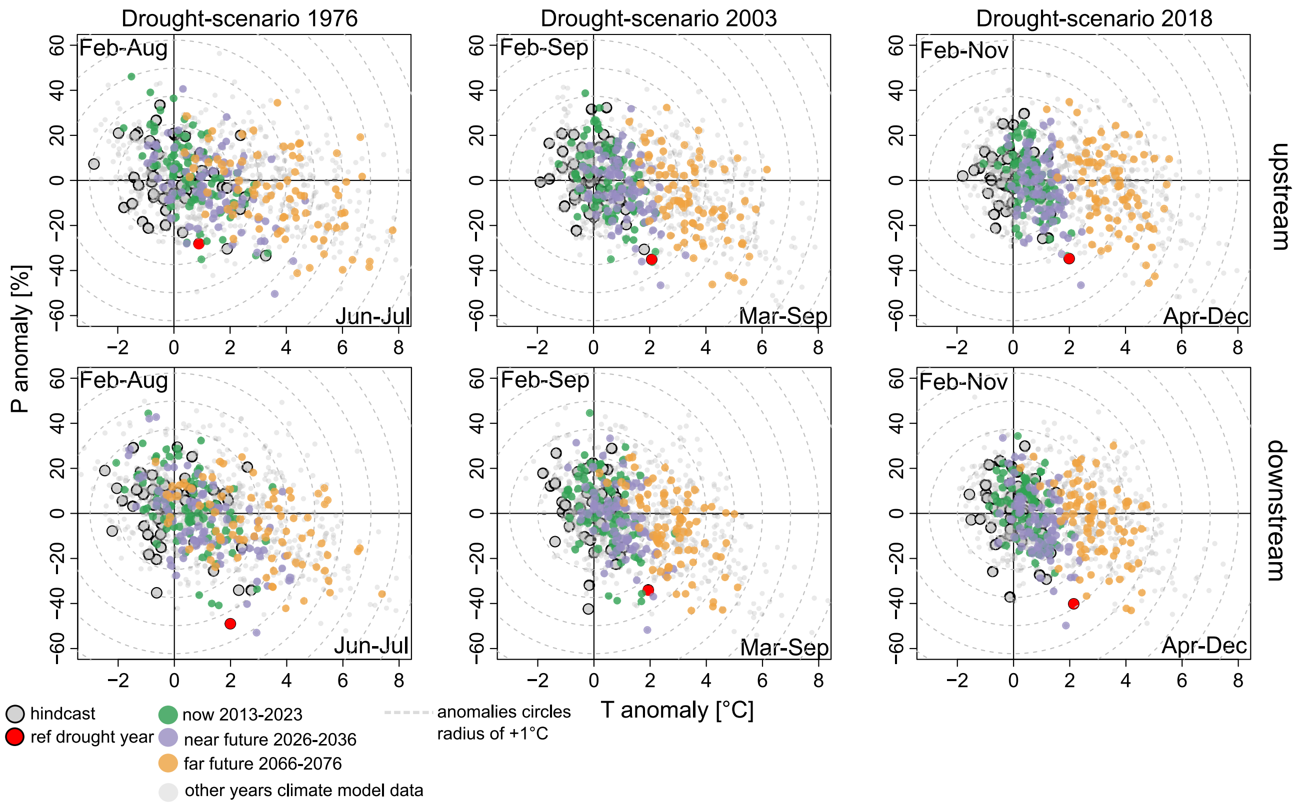

Figure 4. Thermopluviograms of the characteristic meteorological conditions of the three drought-scenario years (columns) for upstream (first row) and downstream (second row) areas of the Rhine basin. For each drought-scenario, the anomalies of P and T are based on different months (see Section 3.4) and are indicated with labels upper-left (P anomaly) and lower-right corners (T anomaly). Anomalies of P and T relate to the mean of 1974–2019 observations or climate model data.

year) was lower than in 2017 (year preceding the nowadays conditions). The effect of more snow in winter on streamflow diminishes around midsummer. For the near future and far future conditions, the seven different climate model projections caused slightly different initial conditions and, as a result, small differences in the relative streamflow changes.

The stress-test simulations do not only allow to investigate how past drought years would look like in future conditions but also how each years' meteorological drought conditions influence the hydrological response. Comparing the "nowadays" runs of drought-scenario years 1976 and 2003, with the streamflow of the reference drought year 2018, keeps the antecedent and catchment and glacier conditions similar, and only the meteorological forcing differs. The high temperatures in drought-scenario 2003 in June and August, caused a higher ice melt contribution compared to the other two drought-scenario years (in nowadays and reference conditions, for 1976 and 2018, respectively), even when glaciers have the same area (Figure S1 in Supporting Information S1). The development of Q_{rain} and Q is similar for the drought-scenario years 2003 and 2018 from around June to October. Q_{snow} is generally higher for the drought-scenario years 1976 and 2018 and can likely be attributed to a combination of high precipitation anomalies in January, and colder temperatures in March in those years compared to drought-scenario year 2003. At Basel and Lobith, the lowest flows occur for the conditions of the year 2018, because of the prolonged precipitation deficit. In the headwaters, the close to normal and cold temperature anomalies in September and October in 2003 may have caused the lowest flow of late summer to have occurred in the year 2003, compared to the conditions of the drought-scenario years of 1976 and 2018.

The comparison of the changed future initial conditions stress-tests with the no-glacier scenario shows that the no-glacier scenario is not always the worst-case scenario (Figures 5, 6, and S2 in Supporting Information S1). This shows that not only changes in ice melt contributions are responsible for the change in streamflow but also changes in the snowpack and antecedent catchment storage. For the Weisse Luetschine headwater catchment, removing the ice component of the streamflow lowers the streamflow almost as much as shifting the

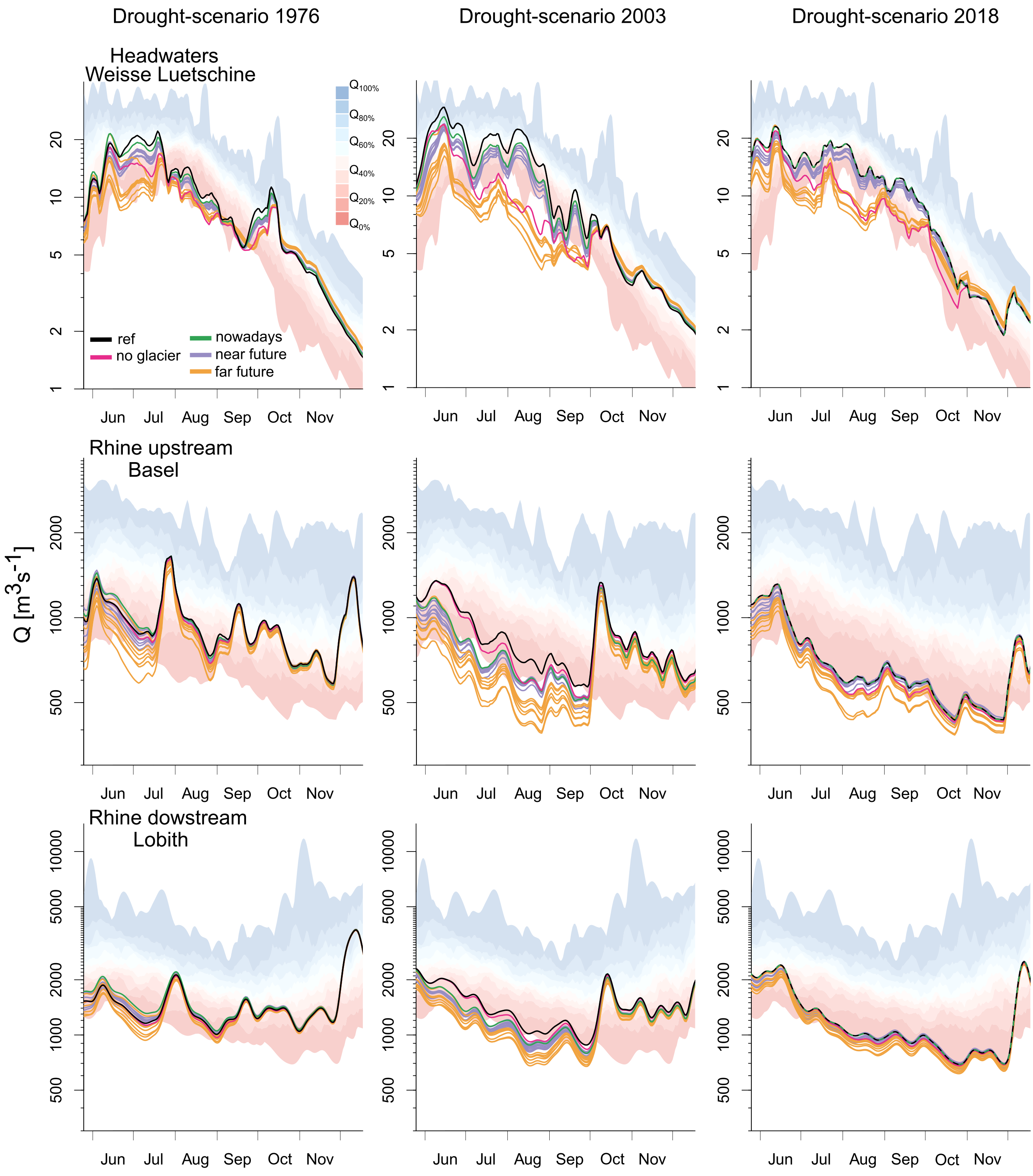

Figure 5. Streamflow during selected drought years (columns) in different conditions: nowadays, near future and far future for three gauging stations along the Rhine (rows). The black line shows the original simulated low flow year. For the near and far future, the seven lines correspond to the seven climate model simulations used as forcing to obtain the initial model states. The streamflow time series are smoothed with a 7-day moving window. Note: logarithmic *y*-axis.

low flow year to far future conditions. In contrast, for the downstream stations Basel and Lobith, especially for the drought-scenario 2003, the no-glacier stress-test streamflow decreases less than the three initial conditions stress-tests (Figures 5 and 6). These results can be explained by different processes. First, the relative ice melt contribution is smaller downstream. Second, in the reservoirs downstream of the headwaters but upstream of

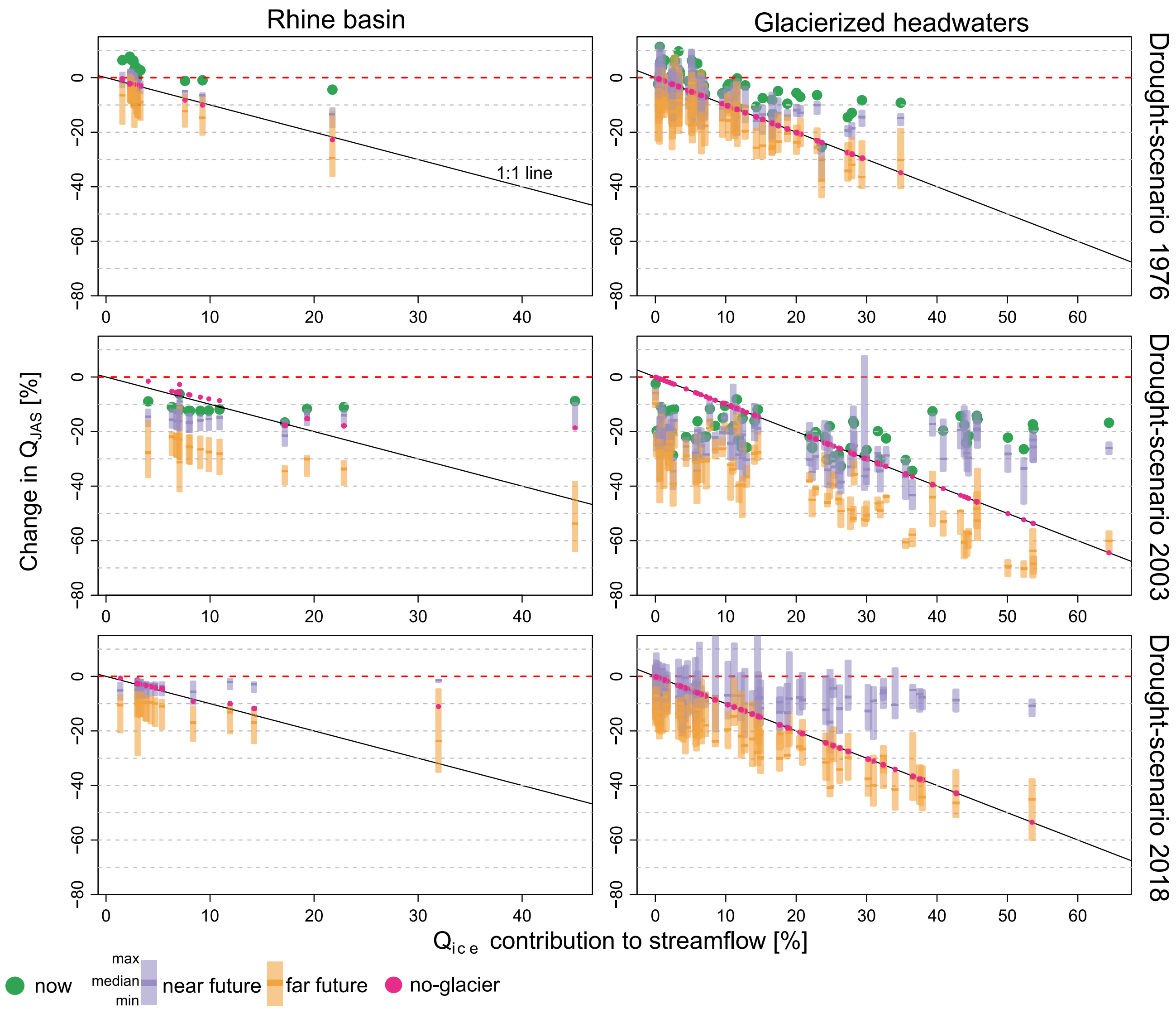

Figure 6. Changes in summer streamflow in the stress-test scenarios for the three selected drought years. The left column shows the different gauging station in the Rhine downstream of the glacierized headwaters, and the right column shows the glacierized headwaters. The changes in summer streamflow for "now," "near future," and "far future" conditions are shown against the relative ice melt contribution to streamflow during the original drought year. The black line shows the 1:1 relation between changes in summer streamflow and the relative ice melt contribution.

Basel, the outflow changes because of the changed inflow (less water because of no Q_{ice}). The snowmelt and rain component are higher in the no-glacier scenario compared to the original run and compensating the missing Q_{ice} component, despite having otherwise the same meteorological and antecedent conditions. Third, besides changes in the ice melt contribution to streamflow, the different initial condition stress-test scenarios also affected the drought years' antecedent conditions of groundwater and snow storage, thereby affecting also the other streamflow components, as opposed to the no-glacier scenario in which antecedent conditions did not change.

In general, the relative changes in streamflow in the stress-test scenarios can be related to the catchments' glacier cover and the Q_{ice} contribution. Thus, the streamflow changes decrease from upstream to downstream (Figure 6). Changes in mean July-September streamflow during low flow years in different future conditions were largest for the year 2003. For the highly glacierized headwater catchments, streamflow reduces up to 40% in the summer when examining drought-scenario 1976 in the far future, and up to 70% and 60%, respectively, for drought-scenarios 2003 and 2018 in the far future. If the 1976 and 2003 meteorological conditions occur in the nowadays situation, flows are simulated to be up to 10%–30% lower. Downstream of the headwaters, changes in summer flow are largest for Brienzwiler in the Aare river (Figures 1 and 6). In Basel, changes are around 5%–15%

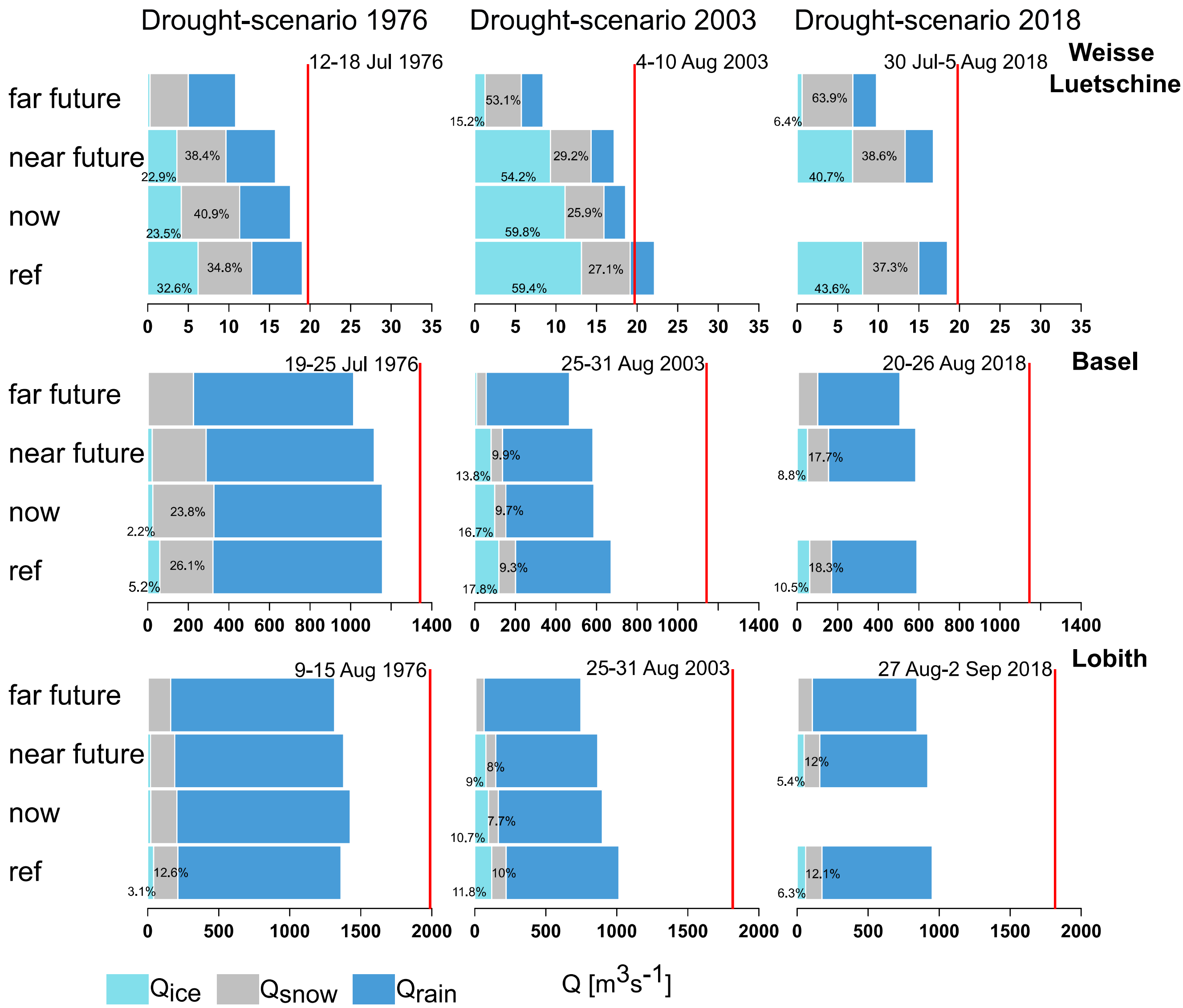

Figure 7. Flow composition of the calendar weekly maximum relative ice melt contribution for the three drought years, in different scenarios and for different gauges. Vertical red lines indicate the average flow of the selected weeks, based on the simulations 1974–2019.

when repeating the drought-scenario years 1976 and 2018 but are larger for the drought-scenario year 2003 (15%–30%) in future conditions (Figure 6). Downstream, at Lobith, the changes are small for the 1976 drought-scenario year but become substantial for drought-scenario 2003, with 15%–25% change, and drought-scenario 2018, with few percent up to 20% change.

Zooming in at a higher temporal resolution, Figure 7 shows that the relative ice melt contribution in the week with the highest contribution, decreases. While weekly flows were extremely low for Basel and Lobith during the three drought years, upstream melt could compensate for the lack of precipitation. In far future conditions, however, flows are reduced to half and well below current normal conditions upstream. Figure 7 shows that all streamflow components change in the stress-test scenarios, but the largest changes occur in Q_{ice}. Weekly ice melt contributions between 3% and 18% for the gauging stations Basel and Lobith during drought years decrease to negligible contributions in the far future.

4.4. Water Use Restrictions During Stress-Test Scenarios

Some of the changes in flow in the stress-test scenarios shown above may seem small, in particular for downstream gauges along the Rhine. However, these changes in already critical low flow situations may have large

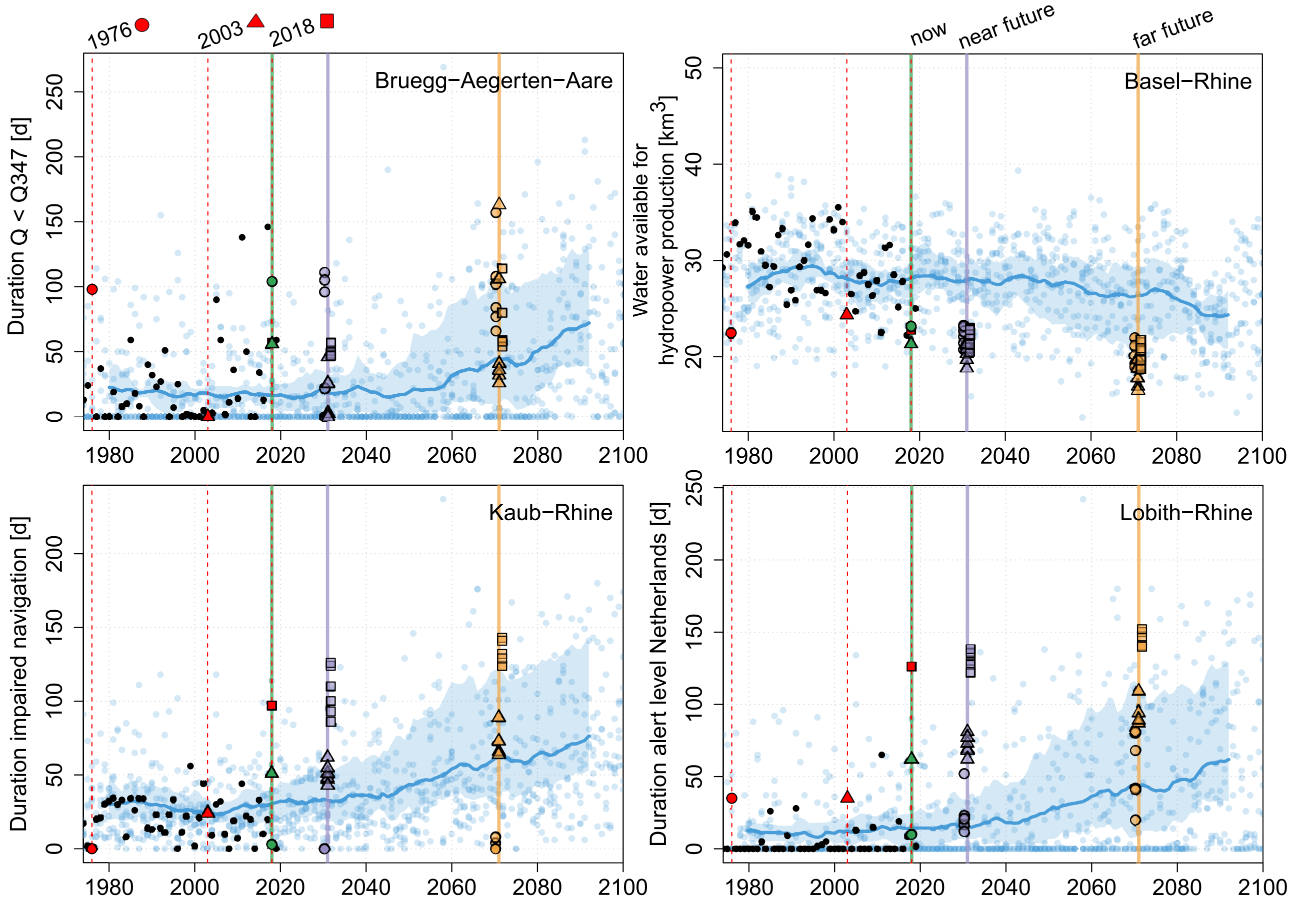

Figure 8. Annual water availability and water use restrictions at several locations along the Rhine: low flow indicator of Switzerland at Bruegg-Aegerten, hydropower production at Basel, Shipping threshold at Kaub and Drought alert level at Lobith. The black dots represent the hindcast simulations, with the three selected drought years indicated in red (reference), and with different symbols. The drought-scenario years in future conditions are indicated with the green, purple, and orange symbols. The blue dots and the blue shaded area show the climate model projections of RCP8.5. The blue line shows the average of the 15 years smoothed seven climate projections and the shaded area the minimum and maximum range.

implications. Figure 8 shows water availability and water use restrictions for different stations along the Rhine and how these change in the stress-test scenarios. At Bruegg-Aegerten, a gauging station in the Aare tributary, 1976 was the year with the longest duration of flow below the Q_{347} threshold (around 100 days), only two other years had low flows for longer, namely 2011 and 2017. In future conditions, the number of days below this low flow threshold increases for all drought-scenario years. The metric is strongly related to flows from January to March in the current conditions, and may eventually also include flows in late summer when flows drop considerably in future conditions and increase in winter. For these reasons, the drought-scenario year 1976 stands out as flows were low in particular during the start of the year 1976. A bit further downstream, at Basel, impacts of drought situations can be felt in terms of hydropower production (Figure 8). The three drought years were among the years with the lowest water availability for hydropower production, with 1976 as the most extreme year. In future conditions, the total flow diminishes and represent future extremes in low water availability for hydropower production. At Kaub, the impaired navigation period was highest for 2018 and negligible in 1976 (Figure 8). In the stress-test scenarios, the impaired navigation period for the drought-scenario years 2003 and 2018 increases with around 50 days from the reference to the far future conditions. Drought-scenario 2003 in near future conditions would make the year the second extreme year, after 2018, with respect to the hindcast period from 1974 to 2019. All the way downstream, at Lobith, 2018 was also the year with the longest duration of the drought alert level (Figure 8). For drought-scenario 1976, the duration of flow below the alert thresholds decreases in the nowadays and most of the near future conditions, but for the other two drought-scenario years the duration increases, more so for the year 2003 than 2018 as the original year already had an exceptional long duration of flows below the threshold.

5. Discussion

5.1. Meltwater Contribution to Downstream Streamflow and Impacts on Low Flows

This study quantified the "what-if"-question "what would happen if past low flow years were to happen again in the future when glaciers have retreated?" The simulations demonstrate that past extreme summer low flow situations worsen in future conditions. How much streamflow changes and the hydrological drought situation aggravates depends on (a) the location in the basin, (b) the timing of reoccurrence, and (c) the specific meteorological conditions.

The relative decreases in summer streamflow during drought years in different future conditions were found to increase with glacier melt contribution to streamflow, which in turn largely depends on the catchments' relative glacier cover. Thus, in general, changes in streamflow in the stress-test simulations were smaller further downstream. However, the flow regimes of glacierized headwater catchments and their downstream basins are very different, with the summer season usually changing from a high to a low flow season from upstream to downstream. Thus, despite smaller relative changes in streamflow, impacts on water availability may be particular profound in the downstream reaches where flow is already critically low during drought summers. The changes in drought characteristics along the river Rhine confirm these patterns, where changes in summer flow around the order of 10%–20% (Figure 6) result in 50% increase in duration of impaired navigation period, e.g. (Figure 8).

The second aspect that determines the exacerbation of past drought years is the timing of reoccurrence. The simulations show that strongest changes are too be expected in far future conditions, when both glaciers in the basin have retreated the most and initial conditions are likely to be drier than nowadays conditions, due to the extreme warming trend. For the drought-scenario years 1976 and 2003, the now and near future conditions do not differ much in terms of glacier area in the basin and the streamflow of these scenarios are therefore close together (Figure 3). The same is true for the reference 2018 drought year and the drought-scenario year 2018 in near future conditions, as they are closer together in time, compared to the reference drought year 2003 and the drought-scenario year 2003 in near future conditions. These years thus have a different benchmark. If similar meteorological conditions as in 1976, 2003, and 2018 occur in the near future, streamflow will already change considerably.

The third control of streamflow changes in the stress-test scenarios is the specific meteorological conditions of the selected low flow years and the specific antecedent storage conditions. The meteorological conditions determine when during the season the lowest flows occur and how much ice could melt during summer, and thus how susceptible streamflow is to changed glacier conditions. In our selected years, the drought year 1976 was mainly characterized by large precipitation deficits, in particular during the winter/spring season, while in the drought year 2003 the extreme heatwave played a role and caused high glacier melt contributions. Antecedent conditions influence the snow and groundwater storage in the catchment, and a large difference in these antecedent conditions between the original and the stress-test conditions results in stronger changes. The results of switching the antecedent year to 2017 instead of 1975 show that if 1976 was not preceded by a dry start of winter in 1975, flows may have been higher. When comparing the years 2003 and 2018, that were both characterized by a heatwave in summer, 2018 turns out to be more extreme, especially when looking at drought characteristics (Figure 8). The reason could be potentially attributed to a decrease in glacier area and glacier melt contribution between 2003 and 2018 (e.g., similar to the case studied by Koboltschnig et al. (2007)), but this can only be tested in a model framework as presented here. Figure S1 in Supporting Information S1 shows that if 2003 and 2018 would occur with the same conditions (glacier area and catchment conditions), flows in Basel and Lobith would have been very similar between June and September, but lower in October and November under drought-scenario 2018 and lower from end of January to beginning of May under drought-scenario 2003 conditions. Q_{ice} was higher under 2003 scenario conditions than under 2018 scenario conditions and the other way around for Q_{snow}. This implies that not only the retreat of the glaciers played a role in the extremeness of the 2018 drought, but also the timing and magnitude of the rainfall anomalies and the summer temperature anomalies.

Overall, the results emphasize that the melt contributions to streamflow diminish in the future and thereby worsen extreme summer low flows downstream in large basins, such as shown here for the Rhine basin. These findings agree with studies from Gosling et al. (2017), Hurkmans et al. (2010), and Marx et al. (2017), that show that low flows will decrease in the Rhine basin under future climate change. However, unlike in our stress-test storylines, these modeling studies did not include the process of glacier retreat and the model setup did not allow to disentangle the role of a changing cryosphere from changing future meteorological conditions.

The findings presented here for the Rhine basin might be expected similar or even stronger in other basins. Whereas the Rhine basin is situated in a relatively wet climate and has a relatively small proportion of glaciers, other basins in Chile and High Mountain Asia, e.g., can contain large ice masses in their mountain water towers and have drier climates, both of which increases the importance of glacier melt for downstream streamflow dynamics (Immerzeel et al., 2020; Kaser et al., 2010; Sorg et al., 2012). Depending on the rate of glacier retreat, the precipitation anomalies and drought conditions and the trend and variability of basin storages, streamflow changes during drought years in future conditions may be more pronounced and potentially leading to large water availability issues (McCarthy et al., 2022; Pritchard, 2019).

5.2. Design of Stress-Test Scenarios

Stress-test scenario's within the framework of event-based storyline approaches have been used in various disciplines and studies to complement probabilistic climate model based projections (e.g., Shepherd et al., 2018; Stoelzle et al., 2020). While the rationale behind different stress-test studies is similar, i.e., aiming for an event-oriented characterization of future risk, implementations vary. To the best of our knowledge, this is the first study that uses this approach in a glacio-hydrological context. Koboltschnig et al. (2007) implemented a similar approach for a glacierized catchment in the Austrian Alps, but the focus was not on risk assessment. Here, we showed the importance of stress-test scenarios for glacio-hydrological systems undergoing rapid changes to understand changes in future risks of extreme low flows and their water use implications. Using only climate model ensembles, the information of specific timing of extreme events in combination with specific glacier states is lost, but important to understand the role of glacier retreat for future low flow risk in large mountain river basins.

Regarding the current design of our stress-test scenarios, a few methodological and process-based considerations can be discussed to aid future design of stress-test scenarios in mountain river basins. The first aspect is the selection window of the meteorological conditions for the stress-test scenarios. Here, the calendar year was chosen. Other selection windows were deemed to be less objective, as, e.g., starting dates of water years vary from upstream to downstream, and different drought events are characterized by different lead-up times. Depending on the importance of snow for summer streamflow, different methodological choices on the drought selection window could lead to slightly different estimates of how streamflow may change in changing conditions. Several studies have shown that winter snow may be important for late summer flows (Godsey et al., 2014; Jenicek et al., 2016; Tague & Grant, 2009), therefore future studies may focus on developing stress-test scenarios that specifically address the question of how changed snow conditions in the winter may affect the development of low flows over the summer from upstream to downstream.

A second aspect is the likelihood of past meteorological conditions in a future climate with a strong warming trend. The results in Figure 4 show that especially toward the end of the century, meteorological conditions can be much warmer than today in the RCP8.5 scenario. However, finding analogs of past drought years in future climate data can be a challenge, because aggregated anomalies do not necessarily need to have the same effect on the hydrological system response and larger ensembles may be needed to test the frequency and characteristics of future extreme drought years (e.g., Brunner et al., 2019; Van der Wiel et al., 2021). Despite this challenge, the warming trend in extreme scenarios (RCP8.5) is evident and future stress-test scenarios should incorporate more extreme (= hotter) droughts and analyze their effect on future low flow risk (Rasmijn et al., 2018; Teuling, 2018; Udall & Overpeck, 2017).

We chose here to obtain the future stress-test conditions from a small climate model ensemble driven by the RCP8.5 scenario and from past conditions (for the "now" situation). In some event-based storyline approaches, "what-if" questions and scenarios can also be designed using imaginary conditions or events, but related to reality (e.g., stakeholder interaction, large ensemble simulations), to investigate extreme rare events. One example in our system could have been to combine an extreme dry winter with an extreme dry summer. However, it is important that physical constrains are not violated. This means that we discourage, e.g., to use changed glacier outlines only to analyze the effect of glacier retreat without changing the catchment conditions that go along with the conditions that lead to glacier retreat.

5.3. No-Glacier Scenario

As a potential "worst-case" scenario, the different drought years were also run in a "no-glacier" scenario. This scenario does, however, not resonate with the above-mentioned physical constrains that should not be violated, and was therefore also difficult to implement. The results show that compared to the other changed conditions scenarios, only removing the Q_{ice} contribution does not result in the strongest changes. These results and the implementation of the "no-glacier" scenario may have several implications for other studies.

As described before, designing the "no-glacier" scenario was not straightforward, as removing a model glacier where it climatically is supposed to exist, results in undesired model behavior. The large snowpack that builds up in that case stores large amounts of meltwater and rainfall and may affect the simulated streamflow in unintended ways, depending on the way processes are conceptualized in the glacio-hydrological model used. However, the "removing-glacier" technique is used in some model studies, to circumvent the need for tracking the glacier contribution through the system (Weiler et al., 2018). In these cases, flow is compared between the run including glaciers and the run without glaciers (e.g., Comeau et al., 2009; Frans et al., 2018; Jost et al., 2012), potentially wrongly attributing the differences in flow to glacier melt contribution only if the snow-to-ice conversion is not taken into account. Other techniques that are used to answer the "what-if" question of completely disappearance of glaciers, relate to the imbalance component of glacier melt (e.g., McCarthy et al., 2022). However, this potentially misses the subtraction of the part of balanced glacier melt that will not be available in case of glacier disappearance and may be important for late summer streamflow.

In our case, the Q_{ice} part of the flow was removed, without removing the glacier in the model configurations. In terms of processes and flow routing, this has a few consequences. Rainfall on glacierized areas contributes to the glacier liquid storage part and contributes directly to streamflow based on outflow parameters that are dependent on the snow on the glacier. However, rainfall on nonglacierized areas infiltrates to the soil and groundwater storages and may contribute to streamflow with a delay. This process also partly explains the changes in Q_{rain} in the future conditions stress-test scenarios. Overall, modeling the processes of no-glacier landscape as a scenario for current climate conditions does not work and we need to be careful discussing such scenarios, unless such a scenario is combined with a future climate and catchment state, in which glaciers do not exist anymore.

5.4. Model Uncertainties

The modeling framework presented here allowed for an integrated assessment of the changing role of upstream glacier and snowmelt for downstream low flows in large river basins. The Rhine basin is a relatively data-rich basin, as opposed to basins that source in, e.g., High Mountain Asia (Lutz et al., 2014; Nepal, 2016). The data availability of streamflow observations in particular is important to constrain and validate the simulations and volumes of water, besides the cryospheric remote sensing data sets that are becoming more widely and globally available.

Modeling streamflow of a large mountain river basin such as the Rhine basin here brings a number of challenges. Streamflow simulations did not always match very well with observations. However, in large basins this can have a number of causes because of the many processes taking place in the basin at the same time. In our simulations, e.g., the year 1976 fitted less good to the observations in Lobith (overestimation), but the other years were simulated well here (Figure 2). In Basel, streamflow was underestimated in the first half year of 2018 but fitted well with observations for the rest of the year. Although it is important to improve modeling efforts, also in these challenging large scale mountain river basins under extreme drought situations, individual tuning of parameters for different parts of the basin was not applied to avoid overfitting of the model. Rather, we aimed for a consistent modeling framework that allows to analyze plausible changes in streamflow under different stress-test scenarios.

The presented model framework divides streamflow in its components Q_{ice}, Q_{snow}, and Q_{rain}. Validating these contributions with observations downstream in the Rhine basin is impossible, as they do not represent particles but effect tracking contributions (Weiler et al., 2018). The estimations can be compared with other studies in the Rhine basin on glacier melt contributions, Junghans et al. (2011) and Huss (2011) e.g., estimated the glacier storage change contribution in August 2003 to streamflow at Basel to be around 23%–31% and at Lobith 15%. These estimates are slightly higher than our estimates (15% and 8.4%, respectively), but we only look at the ice melt contribution, thus excluding snow on the glacier. Moreover, in our approach, daily melt is simulated and tracked through the hydrological system, whereas the other two studies directly compared glacier runoff with downstream streamflow observations.

A specific aspect that needs to be addressed in studies on future low flow situations downstream of mountain water towers is human interactions with the water system, of which reservoir management is one example. Our results showed that with less Q_{ice} water supply from the headwaters in the case of the "no-glacier" scenario the

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outflow of the other streamflow components changes, but based on reservoir operations determined in the past. With future changing streamflow patterns and extremes, reservoir operating rules may change as well. In addition, they may be used to mitigate some of the low flow risk as outlined here in this study if enough water is available during other periods (e.g., Ehsani et al., 2017). Other important facets for model improvement are including changes in vegetation patterns and dynamics (e.g., Duethmann et al., 2020) and multiyear subsurface catchment storage changes (e.g., Fowler et al., 2020), that are currently not well represented in many hydrological models.

6. Conclusion

This study quantified the "what-if"-question "what would happen if meteorological conditions similar to a past observed low flow situations were to occur again in the future?" using a stress-test storyline modeling framework with a special focus on the glacierized headwater catchments of the European river Rhine basin. The simulations demonstrate that past extreme summer low flow situations exacerbate in future conditions. How much they aggravate depends on the location in the basin, the timing of reoccurrence and the specific meteorological conditions of past drought events.

The results emphasize that melt contributions from glaciers and snow to streamflow diminish in the future with glacier retreat and thereby worsen extreme summer low flows downstream in large basins, such as shown here for the Rhine basin. Summer streamflow would reduce by a few percent up to 70% along the Rhine, depending on the gauging station distance from the glaciers, the reference drought year and the timing of reoccurrence. In the headwaters, changes are generally larger. However, changes in summer streamflow do not linearly relate to the Q_{ice} melt contribution, because other processes such as changed initial conditions (groundwater storage and snow) play a role too and vary from catchment to catchment. These findings, together with the results of the no-glacier scenario, warn for simply omitting glaciers in glacio-hydrological simulations to investigate the role of glacier retreat on downstream streamflow dynamics.

Several drought indicators calculated for Basel, Kaub, Lobith, and Bruegg-Aegerten point toward a strong aggravation of hydrological drought impacts, as a result of decrease in summer flow, further exacerbating low flow situations. Water availability for hydropower production would reduce, the impaired navigation period at Kaub may lengthen by up to 2 months and drought alert levels in the Netherlands could double in length, impacting water use. Comparing the drought characteristics of the past years with the future climate model ensemble of RCP8.5, shows that drought impacts as we know them from the years 1976, 2003, and 2018 will occur more often and will be prolonged and more severe.

The stress-test storyline framework enabled both the investigation of future conditions, regarding glacier retreat and catchment states, as well as disentangling the effect of past drought year meteorological and catchment conditions on hydrological drought propagation. In further work, such a framework could be used for attribution of extreme future events with regards to catchment and glacier conditions versus meteorological conditions. As indicated by several studies, past drought events may show a preview of future events that will occur with greater frequency. Thus, the stress-test storylines presented here show a glimpse into future hydrological drought responses that are likely to occur more often and aid communication to stakeholders, which may improve future drought management plans or adaptation strategies. However, droughts are likely to become hotter and the question that remains open is how future droughts will influence the hydrological response and low flows in a mountain water tower context, where glaciers could possibly partly compensate for evaporation and lack of rainfall due to increased melt but are also strongly retreating.

Data Availability Statement

Meteorological station data were obtained from Deutscher Wetterdienst DWD, Bundesamt für Meteorologie und Klimatologie Schweiz, MeteoSchweiz, eHYD (Hydrographischer Dienst und Bundesministerium für Nachhaltigkeit und Tourismus) archive for Austrian data, Koninklijk Meteorologisch Instituut Belgie (KMI), MétéoFrance, DREAL Grand Est and the European Climate Assessment Dataset (ECAD) (Klein Tank et al., 2002). Gridded interpolated meteorological observations for the glacierized headwater catchments were extracted from the TabsD (MeteoSwiss, 2017) and the RhiresD (MeteoSwiss, 2019) products from MeteoSwiss. Climate model data were obtained from EURO-CORDEX, through the ESGF portals of DKRZ and SMHI. Streamflow data were provided by Federal Office for the Environment (FOEN) Switzerland and the Swiss Cantons (Freudiger et al., 2020) and the

German Federal Institute of Hydrology (BFG) and can be requested from them. Glacier outlines were obtained through Fischer et al. (2014), Müller et al. (1977), Maisch (2000), Paul et al. (2011). The HBV-light model can be downloaded from https://www.geo.uzh.ch/en/units/h2k/Services/HBV-Model/HBV-Download.html. The stress-test model simulations are available on FreiDok https://freidok.uni-freiburg.de/ (Van Tiel et al., 2023). The reference simulations for the glacierized headwaters (Van Tiel et al., 2022a, 2022b), as well as the reference simulations for the rest of the Rhine basin (Gerlinger et al., 2023) can be found on FreiDok too.

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