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ORIGINAL ARTICLE

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An ensemble of daily simulated runoff data (1981–2099) under climate change conditions for 93 catchments in Switzerland (Hydro-CH2018-Runoff ensemble)

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Abstract
We present a new ensemble of daily runoff simulations for meso-scale catchments in Switzerland for the period 1981–2099: The Hydro-CH2018-Runoff ensemble. The ensemble contains runoff simulations for 93 catchments in Switzerland covering a wide range of different catchment characteristics governed by pluvial, nival and glacial runoff regimes. The hydrological modelling system PREVAH was thoroughly calibrated and validated for each catchment. The simulations show satisfactory performance with a median Nash-Sutcliffe efficiency of 0.82 in the calibration and validation period. The calibrated parameters were then used to simulate runoff under climate change for each of the 93 catchments. These simulations were driven by the high-resolution new Swiss climate change scenarios (CH2018) consisting of 68 GCM-RCM combinations covering 3 different emission scenarios: RCP2.6, RCP4.5 and RCP8.5. The simulations show good agreement between simulated and observed runoff regimes in the reference period. The Hydro-CH2018-Runoff ensemble is publicly available under http://doi.org/10.5281/zenodo.3937485 (Muelchi, R., Rössler, O., Schwanbeck, J., Weingartner, R., and Martius, O. (2020) Hydro-CH2018-Runoff ensemble (version v1). Zenodo) and can be used for further impact studies.

Conflicts of interest: The authors declare that they have no conflict of interest.

Dataset details

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climate change impact, Hydro-CH2018-Runoff, hydrological modelling, runoff changes

1 | INTRODUCTION

Climate change influences all components of the hydrological cycle mainly due to changing precipitation patterns and increasing temperatures (IPCC, 2013). This also includes water on the Earth's surface such as rivers. Potential climate change-related changes in river runoff volume and runoff regimes may have substantial impacts on many sectors, among them water management, agriculture, tourism, energy production, fishery and ecology. Thus, river runoff scenarios serve as an important basis for adaptation planning and highlight the impact and benefits of potential mitigation measures. They also support governments and planning bodies as well as economy and agriculture in their decision-making.

In Switzerland, climate change will have strong effects on runoff (CH2014-Impacts, 2014) as many catchments in Switzerland are sensitive to changes in air temperatures and precipitation. Climate change-induced changes in runoff have already been observed in the last decades (Weingartner, 2019). Due to the importance of snow and glaciers for runoff generation, seasonal shifts in runoff regimes are expected (Horton et al., 2006; Köplin et al., 2012, 2014). The studies cited above are based on climate change scenarios using a delta change approach. This approach does not capture changes in variability and does not capture the transient nature of climate change. Updated climate change scenarios for Switzerland (CH2018) run with the newest generation of climate models (CH2018, 2018) allow us to address these limitations and to produce a new data set of hydrological scenarios – the Hydro-CH2018-Runoff data set.

The CH2018 climate change scenarios were developed using the statistical downscaling approach 'quantile mapping' (Gudmundson et al., 2012). A previous study found that quantile mapping produces higher and more frequent extremes (Rössler et al., 2019). The CH2018 climate change scenarios are available on high spatial (2×2 km) and temporal (daily) resolution and cover a period of 119 years. Using these climate change scenarios allow for a deeper understanding of changes in runoff and their transient evolution.

The Hydro-CH2018-Runoff data set is part of the Hydro-CH2018 project which is based on a mandate by the Swiss Federal Council and aims to provide information for adaptation to climate change. One of the main goals of this project is to compile new hydrological simulations for Switzerland. The Hydro-CH2018-Runoff ensemble contains the most up to date and comprehensive set of hydrological simulations for 93 catchments in Switzerland. These simulations can be used for hydrological impact assessments or for further impact studies such as agricultural or ecological studies. The data set also serves as a basis in the decision-making process for adaptation planners and politicians.

The schematic overview of the procedure and data involved to produce the Hydro-CH2018-Runoff ensemble is depicted in Figure 1. We extensively calibrated and validated the hydrological modelling system PREVAH (Precipitation-Runoff-Evapotranspiration HRU-related Model; Viviroli et al., 2009) for 93 rivers in Switzerland using observations. The model was then fed with the CH2018 climate change scenarios for Switzerland. The resulting ensemble of runoff simulations are transient in time and cover 119 years (1981–2099), three different emission scenarios (RCP2.6, RCP4.5, RCP8.5) defined by the IPCC (IPCC, 2013; Moss et al., 2010; van Vuuren et al., 2011), and different climate model chains.

2 | DATA DESCRIPTION AND DEVELOPMENT

2.1 | Study area

A total of 93 catchments distributed across Switzerland and thereby covering different climatic, geological and hydrological properties are calibrated and simulated (Figure 2). The most important hydrological characteristics are summarized in Table S1. The average area of the catchments is 314 km^2 and catchment areas range from 14 km^2 to 1,700 km^2. The mean altitude of the catchments ranges between 476 masl and 2,700 masl with an average mean elevation of 1,344 masl across all catchments. 22 catchments are glaciated. The degree of glaciation varies between 0.2% and 22% (see Table S1 for more details).

The catchment selection covers the whole range of runoff regimes in Switzerland (Weingartner & Aschwanden, 1992; Figure 2). The Alpine runoff regimes, in high mountain areas above a mean altitude of 1,550 masl in northern Switzerland and in the highest catchments in southern Switzerland, are mainly glacier and snow driven regimes with low flows in winter and peak flows in summer. Pluvial catchments are predominant in the Swiss Plateau, which are driven mainly by precipitation, snowmelt and evapotranspiration resulting in low flows towards the end of summer/autumn and higher flows in winter and early spring. However, the interannual variability in these catchments is very high due to the variability in precipitation. The lower lying catchments in the southern part of Switzerland follow a pluvial regime with multiple yearly peaks. These regimes are dominated by the precipitation patterns in these areas as well as by snowmelt in spring (Weingartner, 2019).

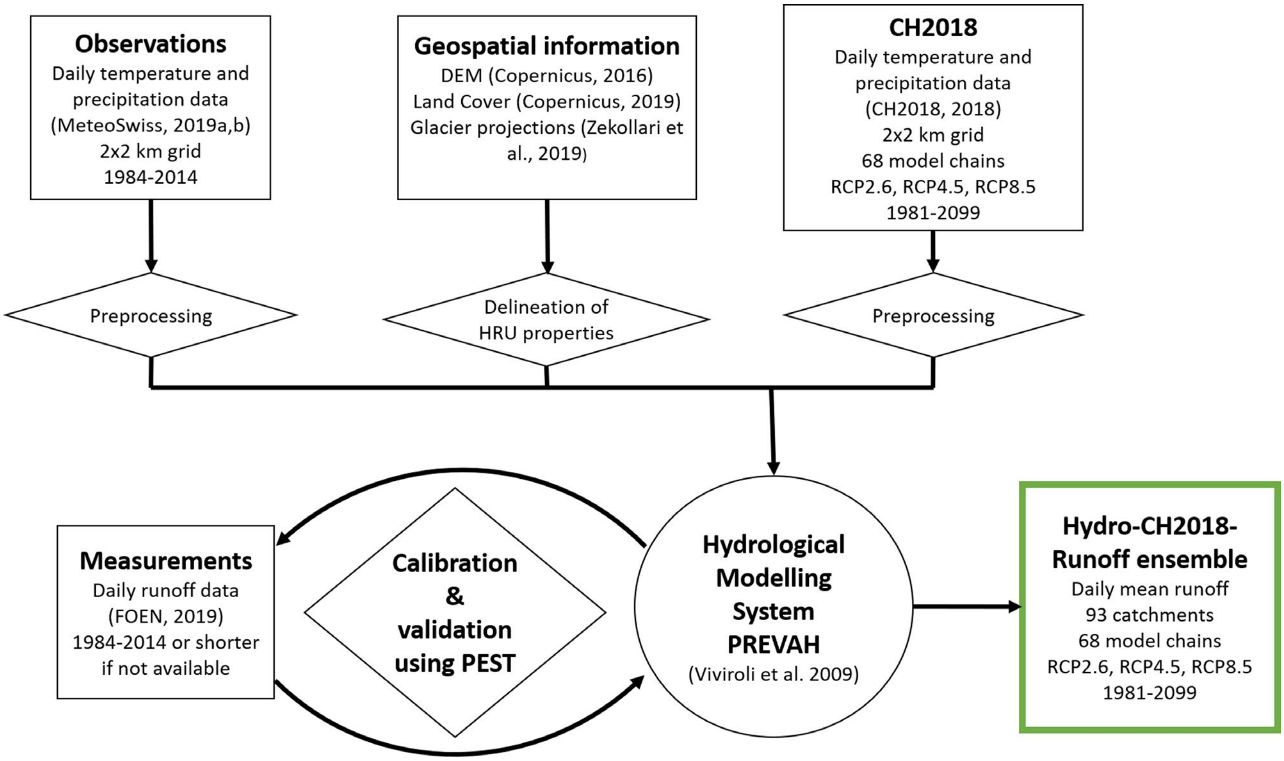

FIGURE 1 Schematic overview of the procedure used in the development of the new Hydro-CH2018-Runoff ensemble

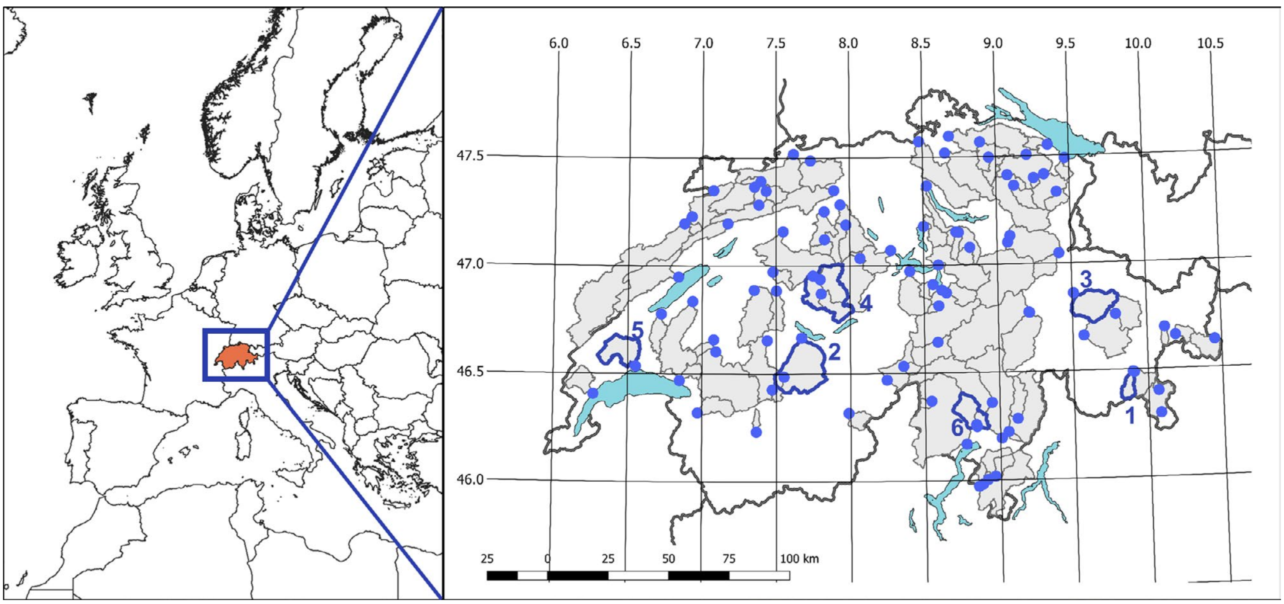

FIGURE 2 Overview of the study catchments and the location of the gauging stations (blue dots). Blue contours indicate the six example catchments: Rosegbach - Pontresina (1), Kander - Hondrich (2), Plessur - Chur (3), Emme - Emmenmatt (4), Venoge - Ecublens (5) and Verzasca - Lavertezzo (6)

2.2 | Input data

2.2.1 | Swiss climate change scenarios CH2018

The Swiss Climate Change Scenarios CH2018 are provided by the Swiss Federal Office for Meteorology and Climatology MeteoSwiss and represent the latest generation of high-resolution climate data for Switzerland (CH2018, 2018). Scenarios for daily temperature and daily precipitation are available for different emission pathways on a 2 by 2 km grid covering the period 1981–2099. CH2018 is based on a top-down approach, downscaling the outcomes of the EURO-CORDEX initiative (Jacob et al., 2014; Kotlarski et al., 2014). In EURO-CORDEX, regional climate models (RCMs) were run for a domain over Europe using the boundary conditions prescribed by Global Circulation Models (GCMs). The EURO-CORDEX simulations were run for two horizontal grid resolutions of approximately 12 km (EUR-11) and 50 km (EUR-44). The forcing is based on three Representative Concentration Pathways (RCP) used in the last IPCC Assessment Report (IPCC, 2013): RCP2.6 assuming compliant mitigation efforts, RCP4.5 assuming non-compliant mitigation efforts and RCP8.5 assuming unabated emissions (Moss et al., 2010; van Vuuren et al., 2011). In CH2018, EURO-CORDEX simulations for temperature and precipitation were statistically downscaled to a 2 by 2 km grid for Switzerland using quantile mapping. Quantile mapping implicitly corrects for potential biases in the RCM. Table S2 gives an overview of the high-resolution GCM-RCM combinations run for the different RCP pathways. Some of the GCM-RCM combinations are run for both spatial resolutions (EUR-11 and EUR-44), and only the higher resolved combinations are used for the ensemble statistics (black crosses in Table S2). In total, this study uses 30 (20 for the ensemble statistics) climate simulations under RCP8.5, 25 (16 for the ensemble statistics) simulations under RCP4.5 and 12 (8 for the ensemble statistics) simulations under RCP2.6.

2.2.2 | Glacier scenarios

Future glacier extents are updated every 5 years to account for glacier retreat under climate change. We used the glacier projections for the Alpine region provided by Zekollari et al. (2019). These projections are based on the glacier evolution model GloGEMflow, which was validated over the European Alps. The projections show that glaciers in the European Alps largely disappear under RCP8.5 scenario while under RCP2.6 approximately one third of the ice volume remains in the Alps (Zekollari et al., 2019). In the 22 glaciated catchments considered in this study, glacier coverage decreases from 0.2%–22% to 0%–11% by end of the 21st century under RCP2.6, to 0%–7% under RCP4.5 and to 0%–2% under RCP8.5. 16 out of 22 catchments still have some glacier coverage by end of the century under RCP2.6 while only 13 and 4 catchments are still partly glaciated under RCP4.5 and RCP8.5, respectively.

The glacier model was driven by the same GCM-RCM combinations from EURO-CORDEX. However, these simulations were downscaled within GloGEMflow and not via CH2018 (Zekollari et al., 2019). For GCM-RCM combinations, which were run on both resolutions (EUR-11 and EUR-44), glacier data are available for the EUR-11 boundary conditions only. In this study, glacier scenarios of the higher resolved models (EUR-11) were also used for the lower resolved model combinations (EUR-44).

2.2.3 | Observational data

Daily discharge measurements at the outlet of the catchments are provided by the Swiss Federal Office for the Environment (FOEN, 2019) and are used for the calibration and validation of the hydrological model. The meteorological data for the calibration consist of observed spatially interpolated gridded daily temperature information TabsD (Frei, 2014; MeteoSwiss, 2019a) and gridded daily precipitation sums RhiresD (Frei & Schär, 1998; MeteoSwiss, 2019b) with a grid resolution of 2.2 km. These data were also used for the 10-year warm-up run of the model prior to the simulation.

2.2.4 | Geospatial information

Geospatial information was used to delineate hydrological response units (HRUs) for each catchment. Information about elevation, aspect, flow direction and slope was derived from the digital elevation model over Europe (EU-DEM; Copernicus, 2016). EU-DEM is available on a 25 × 25 m grid with a vertical accuracy of ±7 m RMSE across Europe. To determine the land use per HRU, the freely available CORINE Land Cover map (CLC2012; Copernicus, 2019) with 44 standard classes and a horizontal resolution of 100m was used. Both elevation and land use information were provided by the Copernicus programme of the European Environment Agency (EEA).

2.3 | Hydrological model

The semi-distributed hydrological modelling system PREVAH (Viviroli et al., 2009) is a conceptual, process-oriented hydrological model (Figure 3). PREVAH was designed for catchments with complex topography to investigate many different aspects of hydrology such as water balance modelling, flood and drought estimation, and forecasting (Viviroli et al., 2009). PREVAH is based on the process-oriented structure of the HBV-model (Hydrologiska Byråns Vattenbalansavdelning; Bergström, 1976; Lindström et al., 1997), but uses hydrological response units (HRUs) for spatial discretization. HRUs are areas with a similar hydrological response and are derived from physical catchment characteristics. All grid elements (500 × 500 m) of one HRU class are located in the same elevation band of 100 m and show similar aspects, land use and soil characteristics.

PREVAH includes various sub-models to account for hydrologically relevant processes such as snowmelt, glacier

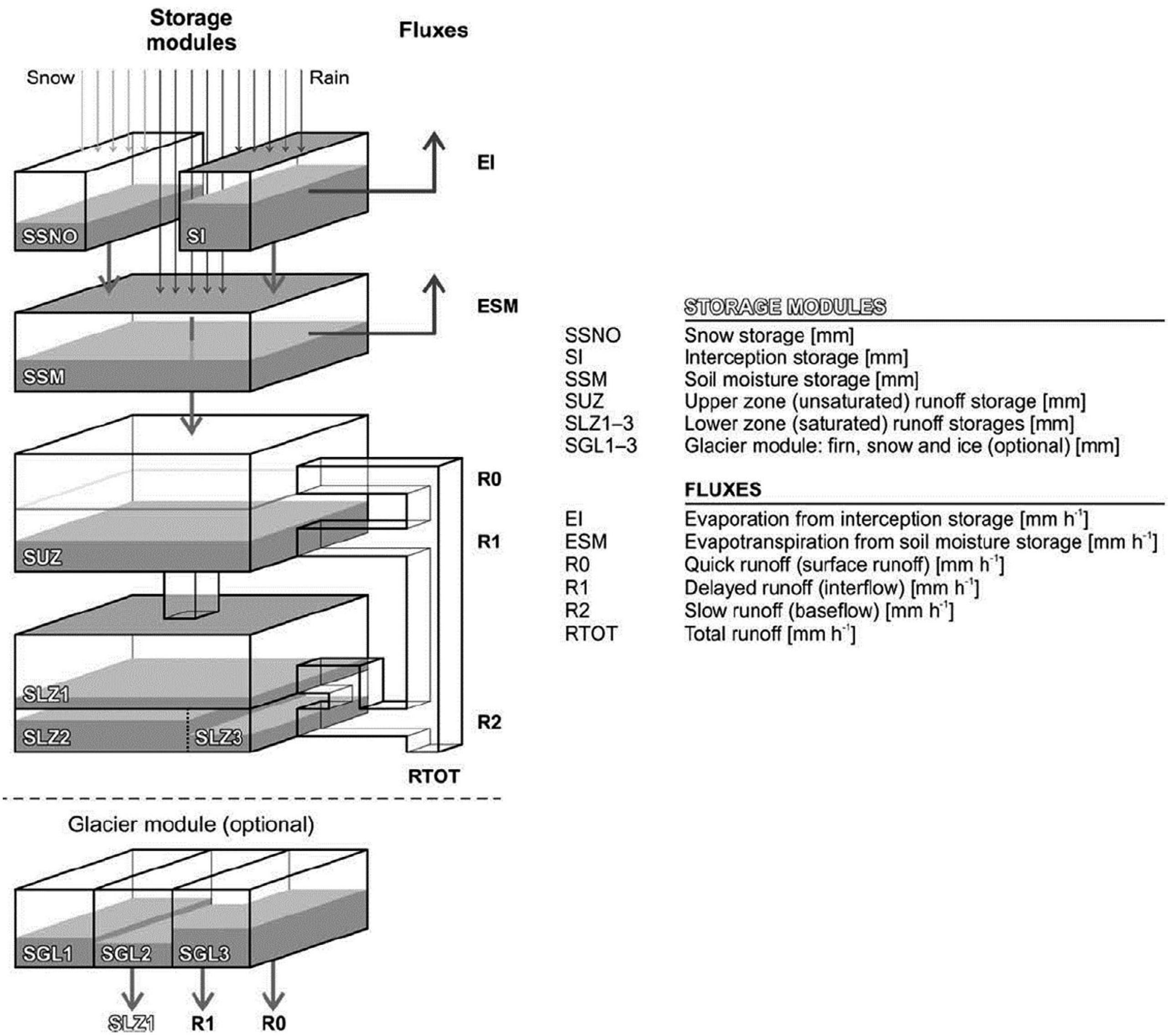

FIGURE 3 PREVAH model structure with storage modules and hydrological fluxes used in this study (adapted from Viviroli et al., 2009)

melt, soil moisture, evapotranspiration, runoff and baseflow generation, and routing components. It also incorporates storage modules for snow, interception, soil moisture, saturated and unsaturated runoff storages, as well as optional storages in the glacier module for snow and ice in case of glaciated catchments. In this study, 13 free parameters for non-glaciated catchments and 2 additional parameters for glaciated catchments were calibrated (Table 1).

Gridded daily mean temperature and daily precipitation totals are available for this study and are used to drive the model. For each catchment, the gridded meteorological input is averaged across elevation zones of 100 m vertical extent. According to the availability and quality of the meteorological variables in the CH2018 scenarios, the estimation of the potential evapotranspiration was calculated using a simple approach based on the equation of Hamon (1961), which requires as inputs only daily temperature data and the maximum sunshine duration (day length).

2.4 | Calibration and validation

Proper calibration of the model for each catchment is important for later simulations under climate change since good performance in the observed period increases the confidence for simulations under different climate conditions (Krysanova et al., 2018). The calibration of the 93 catchments was done using the automated parameter estimation procedure PEST (Doherty, 2005). PEST is an open-source model-independent software to select model parameters resulting in one parameter set as the best fit to observations according to its objective function. Several parameter sets may potentially lead to similar model performance (equifinality; Beven & Freer, 2001). The purpose of this study is to provide an ensemble of runoff simulations for further use in science or for planning purposes. Therefore, the best performing parameter set is chosen for later simulation to limit the number of simulations per catchment.

TABLE 1 List of parameters to be calibrated in PREVAH, the parameters needed for the glacier module are highlighted in italics

Abbreviation	Description	Unit	Parameter range	Initial value
RAINC	Precipitation adjustment	%	–30; 30	0.1
SNOWC	Snow adjustment	%	–20; 20	0.1
T0M	Threshold temperature for rain-snow	°C	–1; 1	0.01
TMFSNOW	Temperature melt factor for snowmelt	mm d^{-1} K^{-1}	0.1; 3	1.5
RMFSNOW	Radiation melt factor for snow	mm h^{-1} K^{-1} W^{-1} m^2	$5*10^{-5}$; $3*10^{-4}$	$1*10^{-4}$
BETA	Non-linearity parameter for infiltration	-	0.5; 5	1.1
SGR	Threshold for quick runoff formation	mm	10; 100	30
K0H	Storage time for surface runoff	h	10; 30	10
K1H	Storage time for interflow	h	50; 150	75
K2H	Storage time for slow base flow	h	1,000; 10,000	2,500
CG1H	Storage time for quick base flow	h	200; 1,000	750
SLZ1MAX	Maximum content of quick base flow storage	mm	25; 1,000	150
PERC	Percolation rate	mm h^{-1}	0.01; 0.5	0.1
CICEMF	Temperature melt factor for ice	mm d^{-1} K^{-1}	0.1; 7	2
CAICE	Radiation melt factor for ice	mm h^{-1} K^{-1} W^{-1} m^2	$1*10^{-5}$; $7*10^{-4}$	$5.1*10^{-5}$

The objective function (Φ) is defined as the squared sum of weighted residuals:

$$\Phi = \sum (w_i r_i)^2 \tag{1}$$

with r_i as the residual of the i'th observation and w_i the weight associated with the i'th observation.

Four observation groups are specified with equal weight (w):

- Observed runoff (Q)
- Transformed observed runoff to give more weight to low flow conditions $((\max(Q) + \min(Q)) - Q_i)$
- Observed monthly mean runoff to account for the regime (Q_{month})
- Observed yearly volumes in the calibration period to account for volume (Q_{year})

The calibration and validation time covers for most catchments the period from 1985 to 2014. Even years were used for calibration and uneven years for validation. In catchments with shorter observed time series, the period from the first fully observed year to 2014 is used for calibration and validation. Again, with even years for calibration and uneven years for validation. Table S1 shows the exact period used for each catchment. The intention of using every second year within 30 years for calibration is to minimize the potential effect of random and non-random trends by using too short calibration periods. Climate change is already observed in the period 1985–2014. PREVAH is therefore trained to also simulate runoff under changing conditions. During the calibration process, PREVAH was run for the whole period while comparing the simulations with observations only for even years. We intentionally chose uneven years for the validation period since some of the years include periods of extreme weather such as very dry summer (e.g., 2003), severe floods (e.g., 2005, 2011) or winters with extreme snowfall and thus extreme snowmelt in spring (e.g., 1999). This leads to the assumption that if the model performs well in uneven years (validation), the calibrated parameters produce stable results also for more extreme or changing conditions.

2.5 | Performance assessment

The results of the calibration were assessed by calculating the Nash-Sutcliffe Efficiency (NSE, Nash & Sutcliffe, 1970) and the Kling-Gupta Efficiency (KGE, Gupta et al., 2009) for the calibration and the validation period, separately. NSE is the mean squared error normalized by the variance of observations (Eq. 2).

$$NSE = 1 - \frac{\sum_{t=1}^{N} (Q_{obs}(t) - Q_{sim}(t))^2}{\sum_{t=1}^{N} (Q_{obs}(t) - \overline{Q_{obs}})^2} \tag{2}$$

where N is the length of the simulation period in days, $Q_{sim}(t)$ the simulated discharge at time t, $Q_{obs}(t)$ the observed discharge at time t and $\overline{Q_{obs}}$ the mean observed discharge.

Kling-Gupta Efficiency decomposes the NSE to three components: correlation, variability bias and mean bias and combines these components into one performance measure according to Eq. 3.

$$KGE = 1 - (r-1)^2 + \left(\frac{\sigma_{sim}}{\sigma_{obs}} - 1\right)^2 + \left(\frac{\mu_{sim}}{\mu_{obs}} - 1\right)^2 \quad (3)$$

where r is the linear correlation between the simulations and observations, σ is the standard deviation of observations and simulations, respectively, and μ the mean of the simulations and observations.

Both performance measures range between -∞ and 1, with 1 being a perfect match between modelled runoff and observed runoff. Values greater than 0 indicate better predictive power than the mean of the observations. NSE tends to emphasize simulations of flood events and therefore strongly penalize for missed peak flows. The NSE was therefore also calculated using square root transformed data. This procedure can then be used as a measure for the overall performance. To accompany the standard performance measures, we also assess the performance by visually comparing the runoff regimes of the simulated runoff with observed runoff. The runoff regimes were calculated by averaging monthly means over the whole period (1985–2014) used for calibration and validation. Based on these measures, we excluded catchments with an NSE < 0.7 in the validation period and/or do not reproduce the regime curve. The remaining 93 catchments fulfilled those requirements and were used for the Hydro-CH2018-Runoff ensemble.

2.6 | Simulation of runoff

Each model simulation was preceded by a 10-year spin up from 1971 to 1980 fed by observations to fill up the model storages. Every catchment was separately simulated with each individual CH2018 climate simulation for 1981–2099 using daily input data. For the whole simulation period, the land use defined for each HRU was kept constant except for glaciated catchments where the glacier extents were updated every five years. When the glacier disappears in an HRU, the land use of the respective HRUs below 3,000 masl was converted to bare soil while the land use of HRUs above 3,000 masl was converted to rock.

3 | CALIBRATION AND VALIDATION RESULTS

The performance measures for the calibration and validation period as well as for square root transformed values are shown in Figure 4 and Table S3. Median NSE values across all catchments for the calibration as well as for the validation period are 0.82. NSE values range from the lowest values of 0.7 to highest values of 0.91 (Figure 4a). The interquartile range in the validation period is slightly higher than in the calibration period, which underlines the good performance of the model for unexperienced runoff observations in the calibration period. The median NSE of square root transformed data is slightly higher than the non-transformed NSE with a median of 0.83 in the calibration period and 0.84 in the validation period (Figure 4a). This is also true for the interquartile range of square root transformed NSE indicating a good overall performance.

The median KGE value across all catchments is 0.89 in both periods and ranges between 0.71 and 0.93 in the calibration period and 0.75 and 0.96 in the validation period. The interquartile ranges of KGE are smaller than for NSE (Figure 4a). The relation between NSE in the validation period and the catchment area and mean elevation is shown in Figure 4b and c to explore potential dependencies between validation performance and catchment properties. No clear relationship between catchment properties and performance can be identified. However, some of the smaller catchments show smaller NSE values than the large catchments (Figure 4b). This may be due to the use of daily precipitation and temperature data.

The validation of the runoff regimes of a subset of six catchments is shown in Figure 5 (for other catchments see Appendix Figures S1–S8). The six catchments represent typical runoff regimes in different parts of Switzerland (see Table 2 and highlighted catchments in Figure 1): Rosegbach – highly glaciated, Kander – partially glaciated, Plessur – high-alpine snow influenced, Emme – pre-alpine snow influenced, Venoge – lowland rain dominated and Verzasca – southern-alpine pluvial.

Figure 5 shows that the control run, fed by observations and modelled with the calibrated parameters (purple), results in similar runoff regimes as the observed regimes (red). The model is able to reproduce the seasonal cycle of the regimes and matches well with the observations. Green shadings show the runoff regime of the simulated runoff driven by the CH2018 scenarios for the reference period 1981–2010 for all models under RCP8.5. For the reference period, the RCP8.5 input should not differ from the climatological forcing.

A visual comparison of the regimes yields the following results: The simulated regimes follow the seasonal cycle of the observed regimes in all catchments. However, patterns of seasonal over- and/or underestimations can be found. For the glaciated catchments Rosegbach and Kander, autumn runoff driven by the CH2018 scenarios is slightly overestimated compared to observations. Such an overestimation can also be found in other glaciated catchments (see Figures S1–S8). The Hydro-CH2018-Runoff ensemble slightly underestimates runoff in late spring in the snowmelt-driven river Plessur. The pluvial catchment Emme shows a slight overestimation in winter in the reference period of the Hydro-CH2018-Runoff ensemble. In the southern alpine river Verzasca, the Hydro-CH2018-Runoff simulations miss the peak in spring likely due to missing snowmelt intensity. Such a bias between

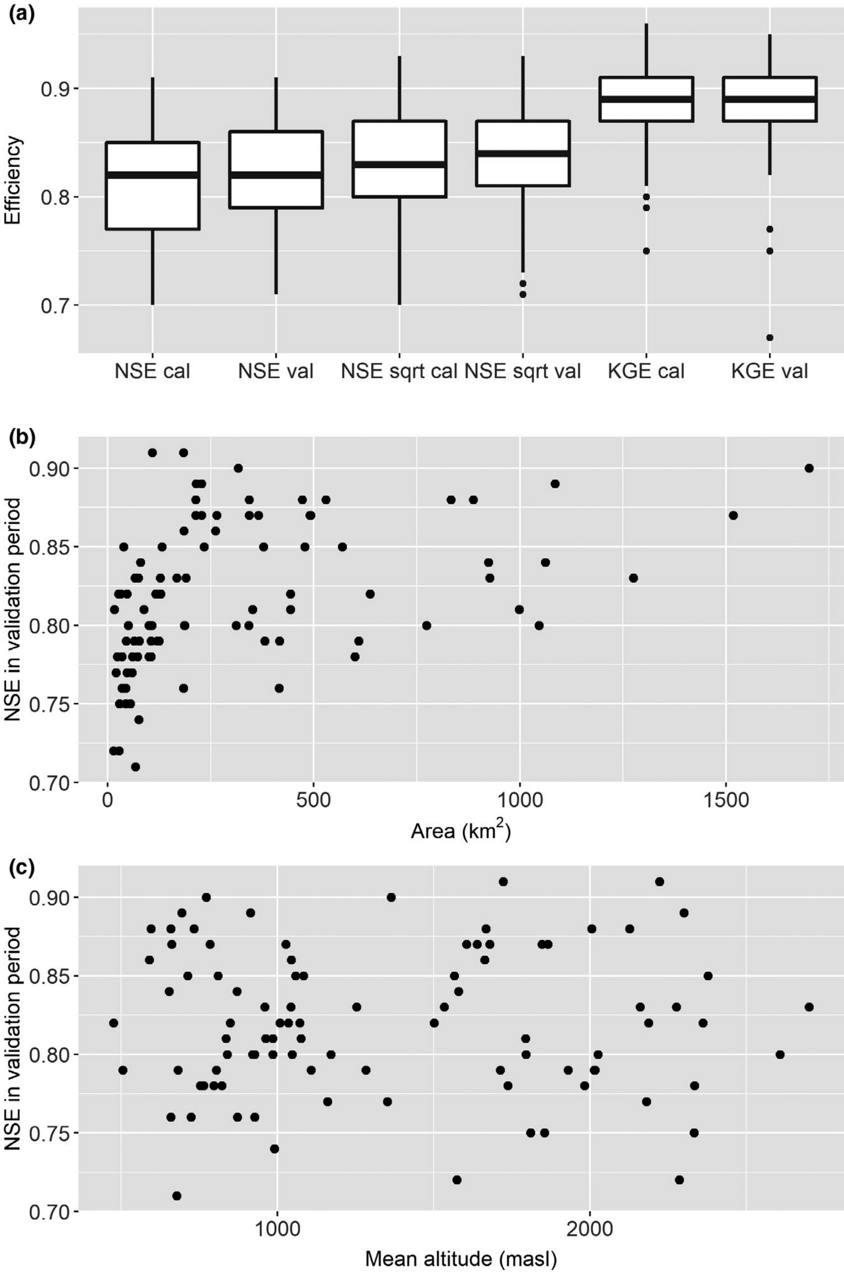

FIGURE 4 Performance of PREVAH for 93 catchments. Performance measures for calibration (cal) and validation (val) periods among all catchments (a), relation of the NSE in the validation period to catchment area (b), relation of NSE in the validation period to mean altitude of the catchment (c)

the Hydro-CH2018-Runoff simulations and the observations in spring is found in six of the southern alpine catchments (Figures S1–S8).

Figure 6 shows an example for the use of the new Hydro-CH2018-Runoff data set. The temporal evolution of the 30-year rolling winter and summer mean runoff for the six representative catchments is shown for the three emission scenarios. Increasing winter runoff and decreasing summer runoff is found in all six catchments, with amplified changes under RCP8.5 scenario compared to RCP2.6 and RCP4.5. The figure also highlights the substantial benefit of using transient scenarios by showing that the runoff response to climate change is not necessarily linear over time. For example, the summer mean runoff of the glaciated catchment Rosegbach increases in the first decades (mainly due to increased glacier melt) and strongly decreases later in the century (due to substantial glacier retreat). Non-linear changes can also be found in other catchments and seasons such as winter mean runoff under RCP2.6.

4 | DATA AVAILABILITY AND REMARKS ON THE UNCERTAINTY

This study provides daily runoff simulations for 93 Swiss catchments and a total of 67 GCM-RCM combinations covering three different emission scenarios: RCP2.6, RCP4.5 and RCP8.5. The daily simulations as well as monthly,

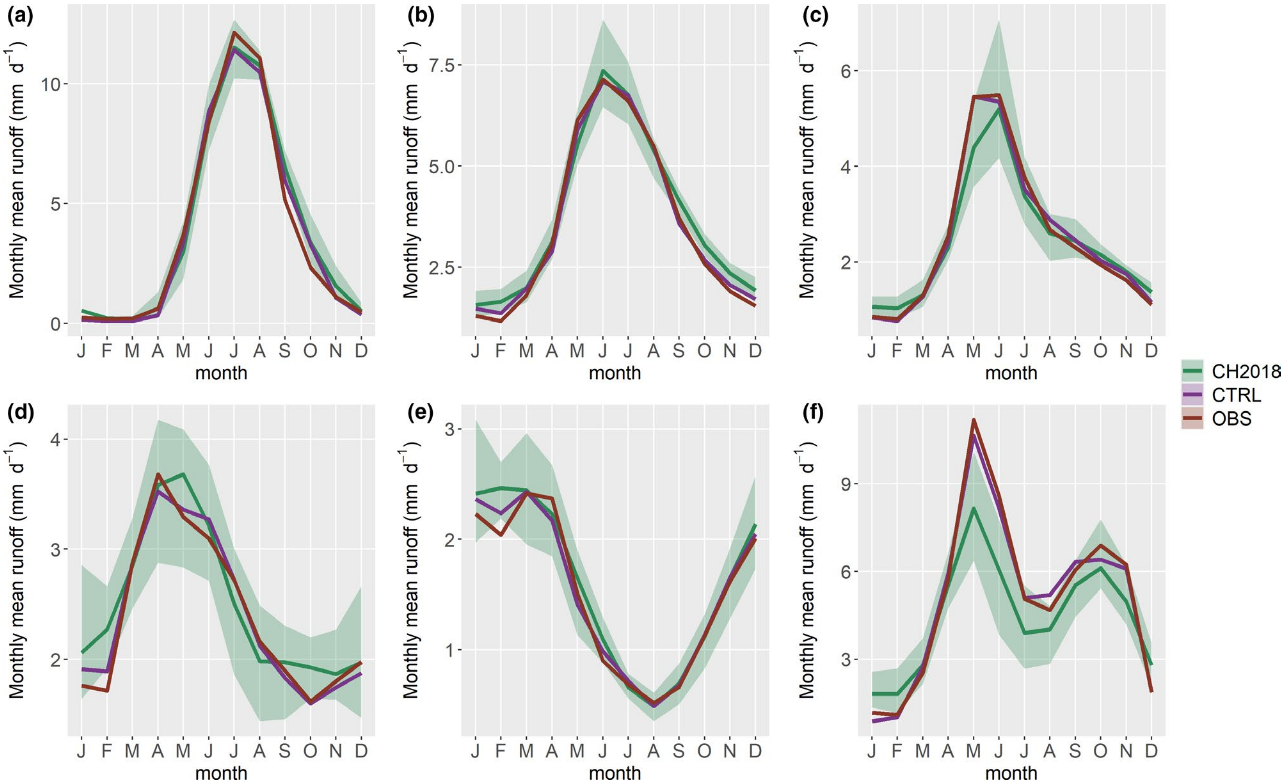

FIGURE 5 Runoff regimes of six representative catchments for observations (OBS, reg) for 1985–2014, control simulations with calibrated parameters (CTRL, purple) for 1985–2014, and simulations driven by the CH2018 scenarios (CH2018, green) for the reference period 1981-2010 (RCP8.5) for Rosegbach - Pontresina (a), Kander - Hondrich (b), Plessur - Chur (c), Emme - Emmenmatt (d), Venoge - Ecublens (e) and Verzasca - Lavertezzo (f)

TABLE 2 Selection of six representative catchments and their main characteristics and regime types

Gauging station	Mean elevation (masl)	Area (km^2)	Glaciation (%)	Regime type[1]
Rosegbach – Pontresina	2,701	67	21.7	a-glaciaire
Kander – Hondrich	1,846	491	5.1	b-glacio-nival
Plessur – Chur	1,865	264	0	Nival alpin
Emme – Emmenmatt	1,072	443	0	Nivo-pluvial préalpin
Venoge – Ecublens	694	228	0	Nivo-pluvial jurassien
Verzasca – Lavertezzo	1,663	185	0	Nivo-pluvial méridional

[1]After Weingartner and Aschwanden (1992).

seasonal and yearly means are available for each catchment and GCM-RCM combination under https://doi.org/10.5281/zenodo.3937485 (Muelchi et al., 2020). Since some of the GCM-RCM combinations are available for different resolutions (EUR-11 and EUR-44), the usage of the higher resolution (EUR-11) is recommended (see Table S2) resulting in a reduced ensemble of 44 GCM-RCM combinations. This avoids giving double weight to single model combinations in the calculation of ensemble statistics.

The Hydro-CH2018-Runoff data set consists of runoff simulations based on the CH2018 climate change scenarios for Switzerland and represent the most up to date simulations for meso-scale rivers in Switzerland. Nevertheless, different sources of uncertainty have to be considered. First, the post-processing and downscaling of the climate model output with quantile mapping assume stationary model biases. Second, stationarity is assumed for calibration, that is, that the calibrated parameters still hold for conditions under climate change. Third, catchment properties including land use were kept constant for non-glaciated catchments during the simulation period. For glaciated catchments, glacier extents were updated every five

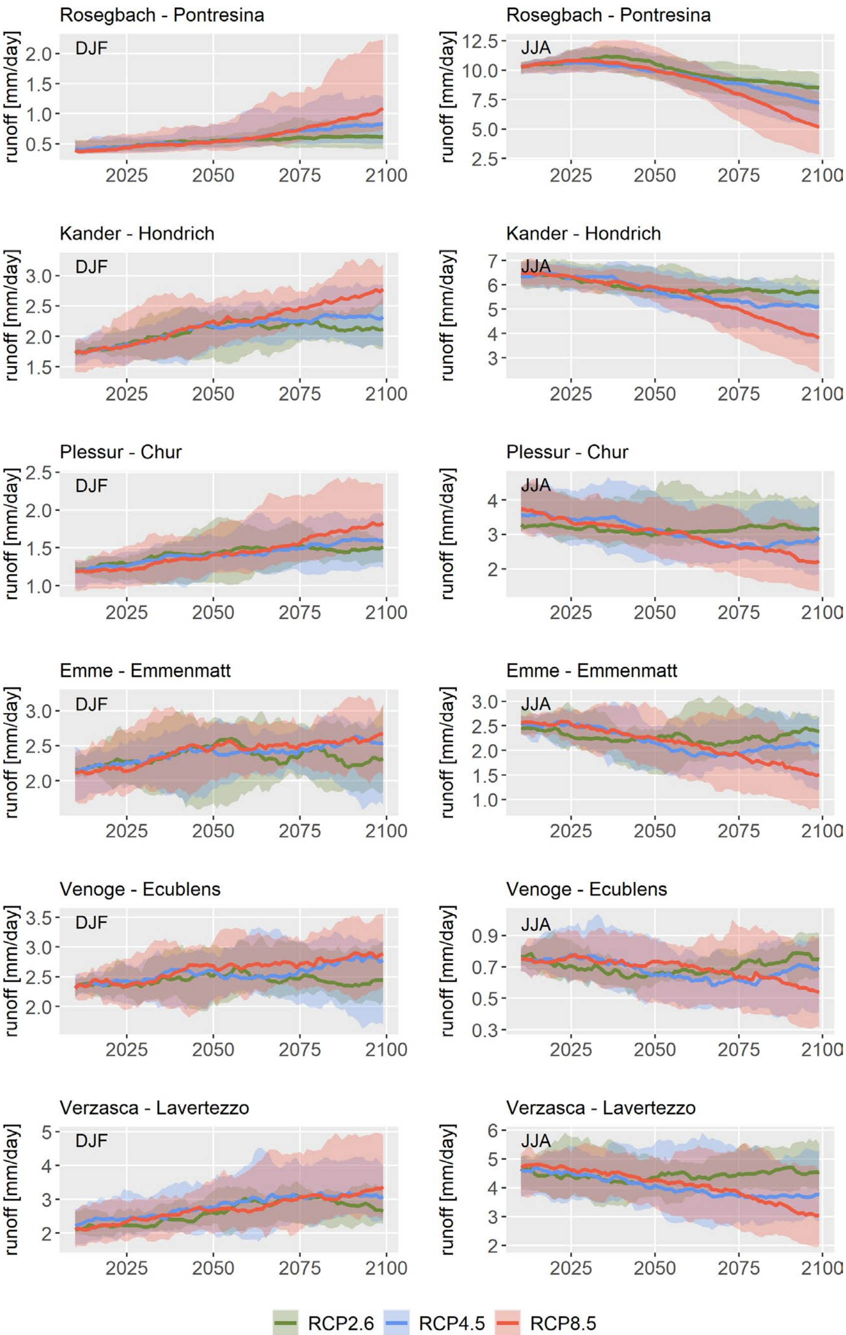

FIGURE 6 Example of use of the Hydro-CH2018-Runoff data set: 30-year rolling means of winter (left panels) and summer (right panels) mean runoff for the six representative catchments and the three emission scenarios. Solid lines represent the multi-model median within an emission scenario and shadings indicate the model spread within an emission scenario

years to account for glacier retreat under climate change (Zekollari et al., 2019). Fourth, the Hydro-CH2018-Runoff ensemble was created using only one hydrological model. A comparison for some catchments with the results of two other hydrological models (PREVAH-WSL and HBV-light) showed a strong agreement on the climate change signal in the runoff among the hydrological models (not shown here). However, the magnitude of change can vary, particularly in summer and autumn in highly glaciated catchments. This is mainly due to the different handling of glacier retreat and glacier melt modelling. Similar differences between models in glaciated catchments were also found in a previous study by Addor et al. (2014).

5 | CONCLUSIONS AND OUTLOOK

A total of 93 catchments distributed across Switzerland covering many different catchment characteristics were successfully calibrated and show satisfactory performance both in terms of NSE and KGE and in terms of reproduction of the runoff regimes. Runoff simulations for these catchments were then fed with the CH2018 high-resolution climate change scenarios for Switzerland. For the first time, transient 119-year long daily runoff simulations are available for a large ensemble of climate models and the underlying RCP2.6, RCP4.5 and RCP8.5 emission scenarios.

The Hydro-CH2018-Runoff data set allows for a comprehensive assessment of climate change impacts on the runoff in Switzerland. The simulations can be analysed for potential changes in runoff indicators and for their timing. The results of such an assessment can be further used as a basis for adaptation planning and negotiating mitigation action. The use of the Hydro-CH2018-Runoff data set is not restricted to hydrological assessments, but the data can also be used for impact studies in other sectors such as agriculture, energy production and ecology.

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OPEN PRACTICES

This article has earned an Open Data badge for making publicly available the digitally-shareable data necessary to reproduce the reported results. The data is available at http://doi.org/10.5281/zenodo.3937485 Learn more about the Open Practices badges from the Center for OpenScience: https://osf.io/tvyxz/wiki.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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