Discharge of mesoscale catchments

Abstract
This map depicts changes in mean monthly, seasonal, and annual discharge and in the low-flow parameters NM7Q and Q_{347} under climate change for the three emission scenarios RCP2.6, RCP4.5, and RCP8.5. The projections are based on the Hydro-CH2018-Runoff ensemble and show the changes for three future periods: 2035 (2020–2049), 2060 (2045–2074), and 2085 (2070–2099). The values for parameter Q_{347} are given according to convention [1], based on 10-year periods, in the middle of the respective period. The focus is on mesoscale catchments. The discharge of large catchments is shown in Map L02, and that of heavily glaciated alpine catchments in Map L03. It should be noted that the three maps differ in the methodology used for their calculation.

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1 Introduction

Projections of river discharge provide an important basis for assessing the hydrological impacts of climate change and for planning and implementing corresponding adaptation measures in various sectors such as agriculture, industry, tourism, ecology, etc. They also highlight the substantial benefits of measures to reduce greenhouse gas emissions. The presented map is based on the Hydro-CH2018-Runoff ensemble [2], which was created within the Hydro-CH2018 project and funded by the Swiss Federal Office for the Environment. The map shows projected changes in the discharge regimes of 91 mesoscale catchments covering areas of 14 to 1700 km^2. The catchments span the different types of discharge regimes from glacial and nival to pluvial [3]. The map depicts changes in the monthly, seasonal, and annual means as well as the low-flow parameter NM7Q over three 30-year periods for three different emission scenarios: one with low (RCP2.6), one with medium (RCP4.5), and one with high greenhouse gas emissions (RCP8.5). The parameter Q_{347} is handled analogously, but with the values based on 10-year periods, in accordance with convention [1].

2 Data and Methods

The Hydro-CH2018-Runoff ensemble includes daily discharge simulations for the period 1981–2099 under the three emission scenarios. The ensemble was simulated using the PREVAH hydrological modelling system [4]. PREVAH was originally designed for hydrological modelling in complex terrain and includes various submodels to account for processes like soil moisture fluctuations, snowmelt, and glacier melt. Potential evapotranspiration was estimated using the temperature-based formula of Hamon [5]. This formula was selected for its simplicity; it only requires temperature as a meteorological input variable. PREVAH was successfully calibrated and validated for each catchment by running it with observed meteorological input data and assessing the simulated discharge values against observed values. The calibration was done using the daily precipitation [6] and temperature [7] grid data sets as meteorological input, along with daily discharge values (Swiss Federal Office for the Environment FOEN [8]). It was performed by means of the PEST algorithm [9] on even years in the period of 1985–2014. The subsequent validation was performed on the uneven years in the same period. The calibration and validation results are satisfactory, with a median Nash-Sutcliffe efficiency of 0.82 and a median Kling-Gupta efficiency of 0.89 across all catchments in both the calibration and the validation periods. In addition, the seasonal changes in discharge within the calibration and validation periods show good agreement with observations.

To simulate discharge for the period of 1981–2099, the new CH2018 Swiss climate change scenarios were used as meteorological input. CH2018 provides daily gridded precipitation and temperature data from 1981 to 2099 at a resolution of 2 km · 2 km. The climate model chains used are listed in Table 1, along with information about their resolution and the underlying emission scenarios (cf. explanatory text for Maps K01/K02). The number of models available per emission scenario is slightly higher for the present map than for Map L02 because the Hydro-CH2018-Runoff ensemble uses only temperature and precipitation as meteorological input data. More information about CH2018, its model chains and its underlying assumptions is provided in the explanatory text of Maps K01/K02. For the simulations, land use in non-glaciated catchments was kept constant throughout the 21st century. In glaciated catchments, glacier extents were updated every five years according to the glacier projections by Zekollari et al. ([10]; shown in Map L04) to account for glacier retreat. Further information about the methodology and performance assessments is given in Muelchi et al. [2]. In terms of indicators of low-flow, the map shows the 30-year mean of the minimum discharge averaged over 7 consecutive days within a year or season (NM7Q), as well as the 5% percentile of mean daily discharge values over 10 years (Q_{347}).

GCM	init	RCM	RCP8.5		RCP4.5		RCP2.6	
			0.11°	0.44°	0.11°	0.44°	0.11°	0.44°
ICHEC-EC-EARTH	r1i1p1	KNMI-RACMO22E		✓		✓		
	r3i1p1	DMI-HIRHAM5	✓		✓		✓	
	r12i1p1	CLMcom-CCLM4-8-17	✓		✓			
		CLMcom-CCLM5-0-6		✓				
		SMHI-RCA4	✓		✓		✓	
MOHC-HadGEM2-ES	r1i1p1	CLMcom-CCLM4-8-17	✓		✓			
		CLMcom-CCLM5-0-6		✓				
		ICTP-RegCM4-3						
		KNMI-RACMO22E		✓		✓		✓
		SMHI-RCA4	✓		✓			✓
MPI-M-MPI-ESM-LR	r1i1p1	CLMcom-CCLM4-8-17	✓		✓			
		CLMcom-CCLM5-0-6		✓				
		MPI-CSC-REMO2009						
		SMHI-RCA4	✓		✓			✓
	r2i1p1	MPI-CSC-REMO2009	✓		✓		✓	
MIROC-MIROC5	r1i1p1	CLMcom-CCLM5-0-6		✓				
		SMHI-RCA4		✓		✓		✓
CCCma-CanESM2	r1i1p1	SMHI-RCA4		✓		✓		
CSIRO-QCCCE-CSIRO-Mk3-6-0	r1i1p1	SMHI-RCA4		✓		✓		
IPSL-IPSL-CM5A-MR	r1i1p1	SMHI-RCA4	✓		✓			
NCC-NorESM1-M	r1i1p1	SMHI-RCA4		✓		✓		✓
NOAA-GFDL-GFDL-ESM2M	r1i1p1	SMHI-RCA4		✓		✓		

Table 1. The model ensemble of the CH2018 climate scenarios results from multiple model runs (simulations) using different model chains. These represent sequences of global and regional climate models (GCMs and RCMs) and are launched on the basis of partly different initial conditions (init). The explanatory text for Maps K01 and K02 provides an overview of all model runs available in CH2018. In the right half of the figure, a ✓ marks model runs that were used in the present study to calculate the ensemble statistics (median, minimum, maximum) – arranged according to emission scenarios (RCPs) and their spatial resolution (0.11° or 0.44°). Comparison of this table with the equivalent figure in other maps (K01/K02, L02, L03, and L04) reveals the differences in the model runs considered. Table implemented on the basis of [11].

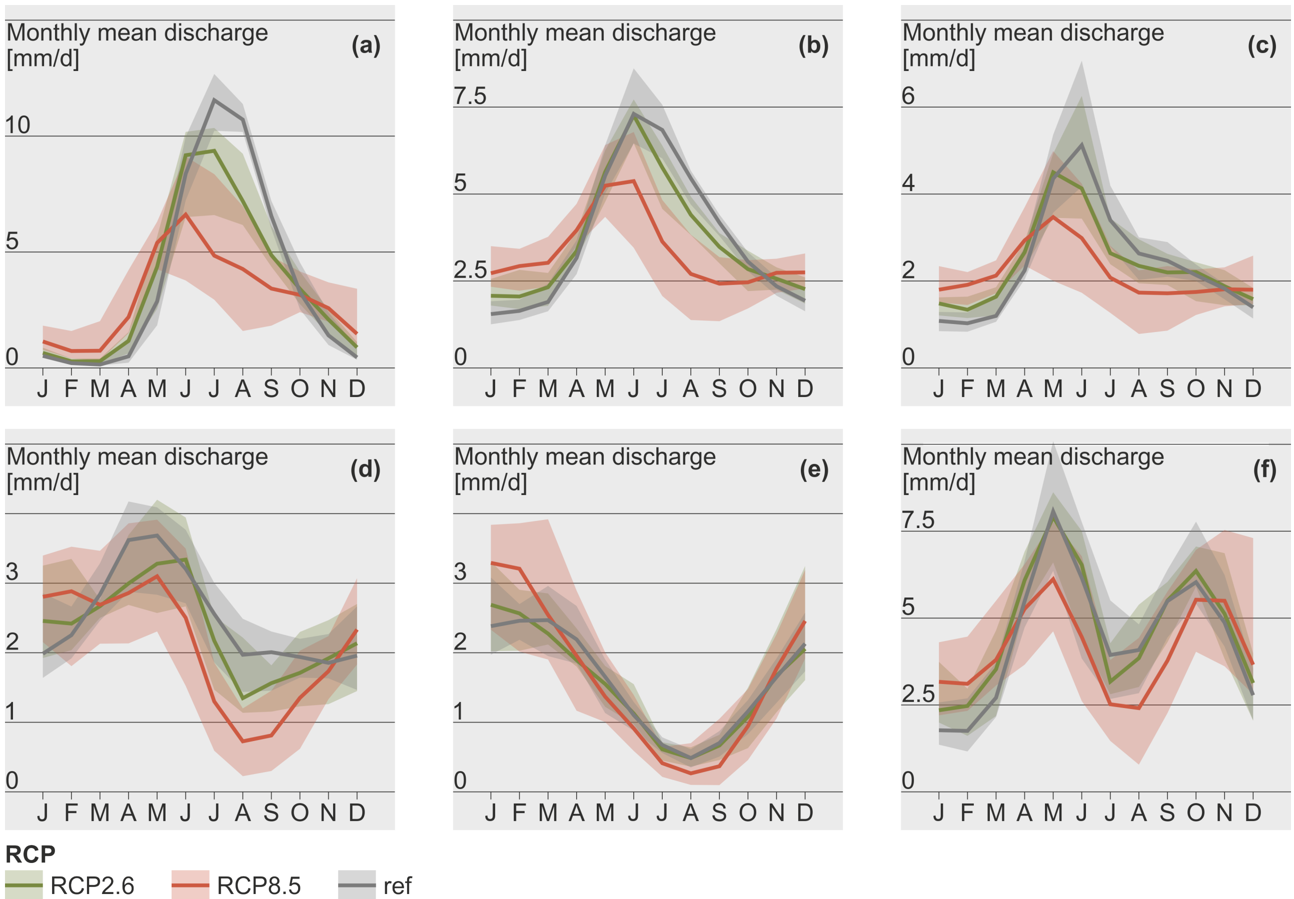

Figure 1. Discharge regimes for Rosegbach (a), Kander (b), Plessur (c), Emme (d), Venoge (e), and Verzasca (f). The lines represent the multi-model median for the reference period (grey), for 2085 under RCP2.6 (green), and for 2085 under RCP8.5 (red). The shaded areas show the full model range [12].

3 Results

The response of mean monthly discharge to climate change shows different patterns for different types of discharge regimes. The following catchments provide a representative overview of the changes in discharge regimes across Switzerland up to 2085 under RCP8.5 and RCP2.6 (Figure 1): Rosegbach–Pontresina (glacial, 22% glaciated), Kander–Hondrich (glacio-nival, 5% glaciated), Plessur–Chur (nival), Emme–Emmenmatt (pluvio-nival), Venoge–Ecublens (pluvial), and Verzasca–Lavertezzo (pluvial, southern Alpine).

Winter discharge generally increases as a result of the increase in winter precipitation and the growing share of liquid precipitation. In contrast, summer discharge decreases; this is due to increased evapotranspiration brought about by higher temperatures, on the one hand, and decreasing summer precipitation, on the other. In glaciated catchments, the reduction in glacier melt due to glacier retreat is expected to intensify the decrease in summer discharge in the long run.

Under RCP8.5 and towards end of the century, the heavily glaciated catchment of the Rosegbach changes from a typical glacial regime to a more nival one, with the highest monthly discharge occurring in late spring or early summer instead of late summer. The mean discharge between June and September drops dramatically due to glacier retreat and reduced snowmelt, whereas winter discharge increases. The contribution of winter discharge to the annual volume nonetheless remains small. The regime of the less glaciated catchment of the Kander likewise shows an increase in winter discharge and a strong decrease in summer discharge, with the highest monthly discharge shifting from summer to late spring or early summer. Unlike in the more heavily glaciated Rosegbach catchment, winter discharge becomes more important in the Kander catchment. In the nival catchment of the Plessur, the maximum monthly discharge also shifts from June to May. The regime curve flattens due to the increase in winter discharge and the decrease in summer discharge; in other words, the difference between maximum and minimum mean monthly discharge decreases under RCP8.5. In the pluvio-nival catchment of the Emme, summer and early autumn discharge strongly decreases, and the typical peak in spring due to snowmelt gradually disappears. The discharge regime of the river Venoge retains its pluvial shape, but its amplitude widens in comparison with the reference period as winter discharge increases and summer discharge decreases. The southern Alpine pluvial regime of the Verzasca, finally, which shows two peaks in the reference period – one in late spring and one in autumn – retains this pattern up to the end of the century, but the peaks become less pronounced. From a qualitative perspective, the direction of change (increase/decrease) under RCP2.6 equals that under

RCP8.5 in almost all months and catchments. However, the deviations of the projected future regimes from those in the reference period of 1981–2010 are significantly smaller under RCP2.6 than under RCP8.5. In addition, the results show that the changes depend strongly on elevation. While alpine catchments are most affected by climate-related changes in winter, spring, and summer, lower-lying catchments are more affected by changes in late summer and autumn. This dependence on elevation is also evident in situations of low-flow. On the Swiss Plateau, in the Jura Mountains, and on the southern side of the Alps, discharge in low-flow situations will decrease in the future. This means that less water will be available, and low-flow situations will become more frequent. In the Alps, where so far the lowest discharge has occurred in winter, discharge during low-flow situations will increase. Thus, the catchments are projected to respond differently to climate change depending on their location and properties. Further results are presented in Muelchi et al. [12] and Muelchi et al. [13].

4 Notes on interpretation and use

The following notes should be kept in mind when using the results of the Hydro-CH2018-Runoff ensemble:

- Hydrological projections are based on a long chain of different models. This chain includes emission scenarios, resulting climate model outputs, as well as hydrological models. Every model in the chain contains uncertainties. The Hydro-CH2018-Runoff ensemble accounts for part of this uncertainty by including a large number of climate model chains and three emission scenarios. However, only one single hydrological model was used, and the use of further hydrological models could potentially lead to (slightly) different results. Nevertheless, comparison of modelling results for the few catchments for which outputs from different hydrological models were available showed good agreement on the impact of climate change on discharge [14].

- It is strongly recommended to use long-term mean values (e.g. of 30-year periods) and the entire model ensemble (all model chains). This reduces the influence of internal climate variability and increases the robustness of the results. The median across all projections constitutes the so-called “best estimate”; but each projection represents an equally likely discharge estimation. Therefore, looking at the median as the best estimate while also considering the value distribution of the entire ensemble gives an indication of the projection’s robustness. It should be noted that the minimum and maximum estimates indicated in the map indeed represent the multi-model minimums and maximums. This distinguishes the present map from the precipitation and temperature maps (K01, K02), where the confidence interval is described by means of the 5% and 95% percentiles. The reason for indicating the minimums and maximums in this map is that the percentiles cannot be reliably determined based on the smaller number of models available for discharge modelling.

- It should also be noted that the number of climate model chains available for each emission scenario differed (Table 1). For RCP2.6 there were eight model chains, for RCP4.5 sixteen, and for RCP8.5 twenty. These differences in ensemble size can influence certain analyses (e.g. ensemble statistics).

5 Example of application

The map L01 shows all 91 stations for which discharge projections are available. A click on one of the stations and then on the link “Discharge scenarios” leads to a set of tabs with four graphs depicting parameters that illustrate the calculated future evolution of discharge in the corresponding catchment. A fifth tab contains a compilation of the underlying data.

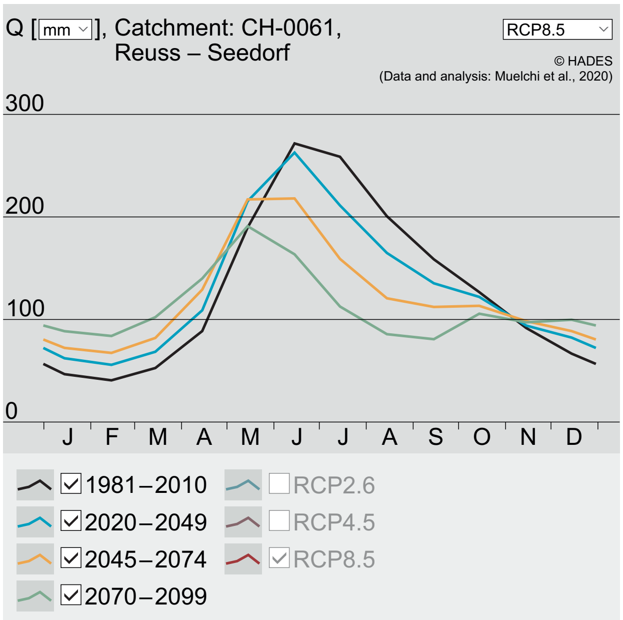

Figure 2. Reuss–Seedorf: Changes in the discharge regime up to the end of the 21st century

The first tab, labelled “Discharge regime”, shows the monthly and seasonal mean discharges. It is possible to compare the regimes for the different periods and emission scenarios. To obtain a better overview, individual curves and the confidence interval can be displayed or hidden by clicking on the checkboxes in the legend. In addition, it is possible to change the unit along the y-axis from absolute values [mm] to relative values [%]. The latter refer to the model outputs for the reference period. Finally, the desired emission scenario or time period can be selected in the top centre of the graph. Figure 2 shows the development of mean monthly discharge for different time periods using the example of the Reuss at Seedorf under RCP8.5: while discharge is expected to decrease during the summer months, it is expected to increase in winter.

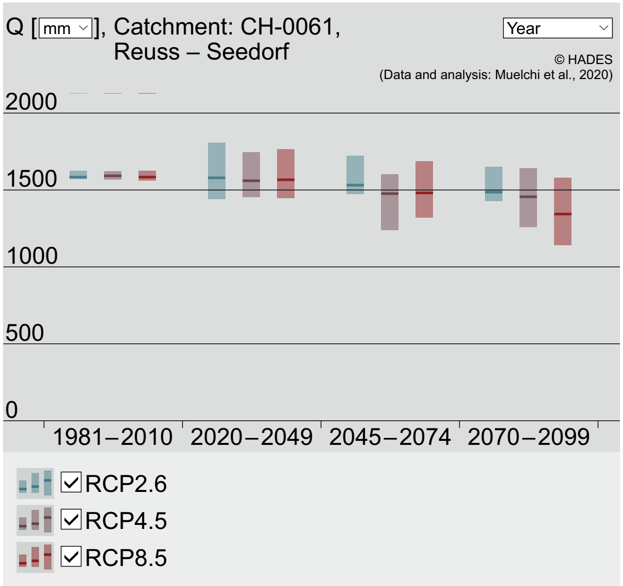

Figure 3. Reuss–Seedorf: Reduction in annual discharge up to the end of the 21st century for RCP2.6 (blue), RCP4.5 (purple), and RCP8.5 (red)

In the second tab, labelled "Mean discharge", it is possible to compare the development over time of mean discharges for individual months or seasons, as well as the annual discharges, for the three emission scenarios. Figure 3 shows that the mean annual discharge of the Reuss at Seedorf is projected to decrease. This indicates that the reduction in summer discharge is stronger than the increase in winter discharge.
In the same way, tabs three and four show the future development of the low-flow parameters NM7Q and Q_{347}, respectively.
The fifth tab, "Underlying data", summarises the underlying precipitation, temperature, and glacier scenarios used for modelling discharges for the relevant catchment. This information can be used for further interpretation of the discharge scenarios. In the above example, these figures indicate an increase in winter precipitation combined with higher temperatures (more discharge during winter) and a decrease in summer precipitation combined with shrinking glaciers (less discharge during summer).
Lastly, it is possible to visualise the spatial patterns of the changes for catchments of similar size. To do this, select "Catchments" in the left-hand sidebar under L01 and define the desired catchment size using the drop-down menu. Now the desired discharge parameter (MQ, NM7Q, Q_{347}) and the desired emission scenario, time period, etc. can be chosen in the right-hand sidebar. Figure 4 shows the relative changes in spring discharge towards the end of the 21st century under RCP8.5. In spring, lower-lying catchments show a decrease in discharge, while glaciated catchments at higher elevations show an increase.

6 Versions

Table 2. Versions

Version	Description
v1.0 (2020)	The dataset and the underlying methods are described in Muelchi et al. [2]. Data available at: https://doi.org/10.5281/zenodo3937485
v2.0 (2022)	Addition of low-flow parameters NM7Q and Q_{347}. Adjustment of map title.

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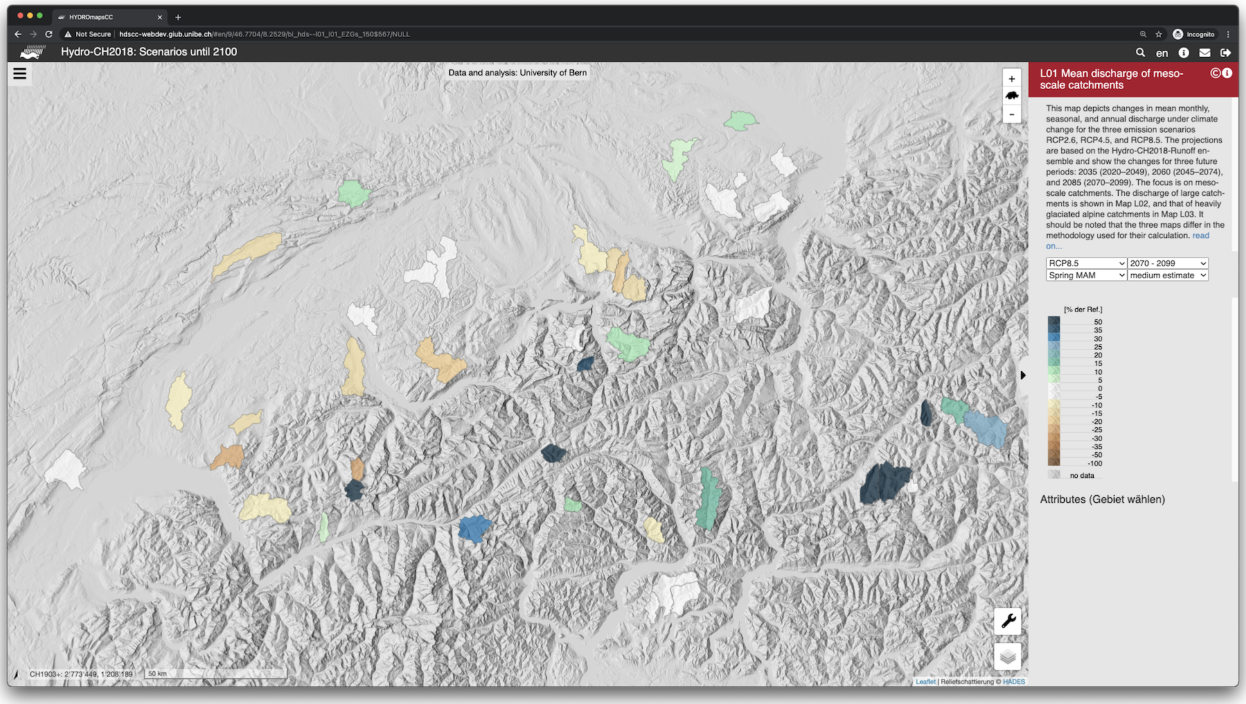

Figure 4. Relative change in spring discharge towards the end of the 21st century under RCP8.5

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