Mean discharge of large catchments

Abstract
This map shows changes in mean monthly, seasonal, and annual discharge under the three emission scenarios RCP2.6, RCP4.5, and RCP8.5 for the three future periods of 2020–2049, 2045–2074, and 2070–2099 in comparison with the reference period of 1981–2010. The focus is on the discharge of large catchments, most of which have a surface area > 1000 km^2. The discharge of mesoscale catchments is addressed in Map L01, 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

The global climate is changing. Humans have caused greenhouse gas concentrations to grow at an increasing rate in recent decades, leading to a global temperature rise [1] with corresponding impacts on the cryosphere. As a result, precipitation patterns are also changing [11]. Precipitation is projected to increase in winter and decrease in summer ([1]; see Map K01). This will directly affect discharge. Indeed, summer precipitation has already declined over the last forty years in various catchments [2]. Low discharge or even water scarcity are predicted to occur in Switzerland mainly in the summer, with the lowlands of the Swiss Plateau likely to be more strongly affected than Alpine regions [3]. Discharge scenarios are important in enabling better – and above all quantitative – estimates of future changes in discharge as a resource.

2 Data and methods

For the present Map L02, the mean discharges of large catchments were simulated using the spatially explicit version of the hydrological model PREVAH (Precipitation-Runoff-EVApotranspiration-HRU related Model) at a resolution of 200 m · 200 m [4]. The model parameters were calibrated, validated, and regionalised for Switzerland already in the studies of Viviroli et al. [5], Viviroli et al. [6], and Köplin et al. [7]. From these, a complete set of gridded parameters at a spatial resolution of 2 km · 2 km was compiled and used by Bernhard and Zappa [8] and Speich et al. [4]. They used the Kriging method for spatial interpolation. The PREVAH parameters employed in computing the present map were taken from this parameter set.

Precipitation, temperature, relative humidity, global radiation, and near-surface wind from representative MeteoSwiss stations from the period of 1975–2016 served as meteorological model input. The meteorological data were spatially interpolated using an altitude-dependent regression and a distance-dependent interpolation [5]. For land use and the digital elevation model, land use statistics from the Swiss Federal Statistical Office were employed (GEOSTAT; Version 1992/97). The snow measurements used are from the Intercantonal Measurement and Information System (IMIS) and the WSL Institute for Snow and Avalanche Research SLF [9]. The Federal Office for the Environment FOEN provided daily discharge data for the calibration and validation of the model. Prior to use, the meteorological data were spatially interpolated by means of an altitude-dependent regression and a distance-dependent interpolation [5].

Future glacier extent was calculated using the method developed by Zekollari et al. [10] and already employed by Brunner et al. (2019) for discharge modelling (see also Map L04).

CH2018 data [11] served as the input for modelling future mean discharges. The outputs of the climate models were downscaled to the stations (see "Daily Local" in CH2018). A total of 39 model chains based on the emission scenarios RCP2.6, RCP4.5, and RCP8.5 were used (see Table 1). This model selection is slightly smaller than that used for Map L01 because the calculation of evaporation requires additional variables (such as wind) that are not available in all climate models.

The discharge simulations pertain to four periods: the reference period (1981–2010), the near future (2020–2049), the medium-term future (2045–2074), and the distant future at the end of the 21st century (2070–2099). The confidence interval for each RCP was derived from the simulations of the model chains belonging to that RCP.

3 Results

Regardless of the region or emission scenario, the results point to an increase in winter and spring discharge and a decrease in summer and fall discharge. Mean annual discharges for the 30-year periods tend to decrease across all three RCPs up to the end of the century. However, this trend is less pronounced than that of seasonal changes.

In the large alpine catchments of the Rhône and Inn, the influence of snowmelt and especially glacier melt gradually declines in the course of the 21st century. In combination with the reduction in summer precipitation

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, L01, L03, and L04) reveals the differences in the model runs considered. Table implemented on the basis of [11].

(Map K01), this leads to a decrease in summer discharge; it is most pronounced at the end of the century and under RCP8.5. Between December and May, the scenarios generally show an increase in discharge.

Along the Aare, from its upper to lower reaches, one sees roughly the same pattern of discharge changes occurring up to the end of the century: an increase in winter discharge due to higher temperatures and a light rise in precipitation, as well as a decrease in summer discharge due to lack of precipitation (K01) and, especially towards the end of the century, very little glacier melt. The effect of these discharge changes in the lower river reaches is that although, under RCP8.5, maximum monthly discharge levels continue to occur in early summer up to the end of the century, a split becomes evident, with similarly high monthly discharge levels between December and June and low monthly discharge levels between July and November. Particularly notable is that the lowest monthly discharges no longer occur in winter, but increasingly in summer – depending on the RCP and time period considered. The same patterns are visible in the more alpine-influenced upper river reaches, for example in the Aare at Thun. As the influence of glacier melt is relatively high here, the dramatic retreat of glaciers – especially under RCP8.5 – leads to a very strong reduction in discharge from July to September. The same holds for the upper and lower reaches of the Reuss and Limmat rivers. Along the upper and lower reaches of the Rhine, the pattern is essentially same as along the Aare.

In the Rhine at Basel, where it drains the entire north side of the Swiss Alps, including alpine, foothill, and lowland catchments, the changes described above are clearly visible: increasing discharge in winter, earlier discharge in spring, and decreasing discharge in summer. Interesting to note is that beginning with the period 2020–2049, under all emission scenarios, the minimum monthly discharges shift from winter to summer. Overall, the changes in mean monthly and annual discharges up to the end of the century, in percentage terms, are less pronounced in large catchments that encompass alpine, foothill, and lowland catchments than in the catchments of the Alpine regions. The main reason for this is that the Alpine regions are more affected by the higher temperatures (K02) and their influence on snowmelt and glacier melt (see also L04).

4 Notes on interpretation and use

The following notes should be kept in mind when using the map: 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. These uncertainties can be addressed to some extent by using a large number of climate models and three emission scenarios as the basis for hydrological modelling. However, only one single hydrological model was used, and the use of other hydrological models could potentially lead to different results. Nevertheless, comparison with other studies (see Map L01) showed good agreement regarding the signs of the change signals.

Since individual climate simulations represent just one possible climate outcome, and every model is structured slightly differently, it is important to remember that each simulation only represents one possibility out of the broader ensemble. Thus, it is recommended to look at the entire model ensemble (confidence interval) and to use long-term mean values (e.g. of 30-year periods). This makes it possible to estimate the robustness of the results and to reduce the influence of internal climate variability. For this reason, in addition to showing the median of all model runs – also referred to as the “medium estimate” – the map presents the minimum and maximum estimates of the ensemble. These provide an indication of robustness by revealing the strength of agreement between individual model runs. The minimums and maximums shown in the present Map L02 cannot be compared directly with those shown in the precipitation and temperature maps (K01, K02), which correspond to 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.

The range of all large-catchment discharge scenarios may be viewed as the possible future water supply for each scenario period. However, caution is advised when interpreting the absolute values of individual discharge scenarios [mm], since the reference period discharge scenarios (simulations using the meteorological data from CH2018) can deviate more or less strongly from the reference period control simulations (using measured meteorological data), and these in turn can deviate more or less strongly from the reference period measurement data. One reason for the deviations is that the influence of lakes in large catchments was only roughly approximated in the hydrological model by representing lakes as single linear reservoirs. Weir structures used to regulate lakes were not implemented in the model. Other reasons include various uncertainties in the entire model chain as well as in the measured data. For this reason, attention should be given primarily to the changes between the scenarios.

5 Example of application

Map L02 shows the 25 stations for which discharge scenarios are available. To navigate to the two graphics showing possible future discharge development, click on one of the stations and then on the link “Discharge scenarios”.

The first tab, labelled “Discharge regime”, shows the monthly 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 change values [%]. Finally, the desired emission scenario or time period can be selected in the top centre of the graph. Figure 1 shows the development of mean monthly discharges up to the end of the 21st century using the example of the Aare at Untersiggenthal under RCP8.5. While a decrease in discharge is expected for the summer months, a slight increase is predicted for the winter months.

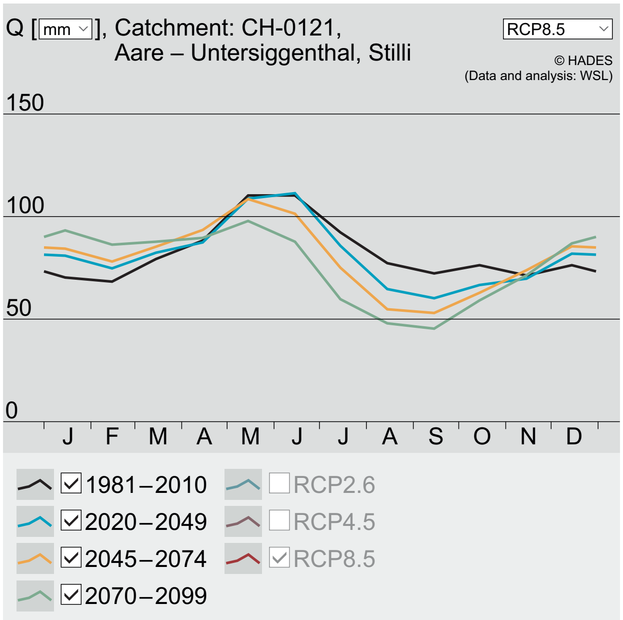

Figure 1. Aare–Untersiggenthal, Stilli: Changes in the discharge regime up to the end of the 21st century under emission scenario RCP8.5, beginning in black (reference period) and spanning blue (2035) and yellow (2060) to end in green (2085)

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 2 shows that the mean annual discharge of the Aare at Untersiggenthal tends to decrease slightly. The decrease in summer discharge and the increase in winter discharge practically cancel each other out.

The third 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, the figures indicate an increase in winter precipitation combined with higher temperatures (more discharge in winter) and a decrease in summer precipitation (less discharge in summer). The glaciated area of this catchment currently already stands at only 1.5%, making it relatively minor in importance.

Lastly, it is possible to compare the spatial patterns of discharge changes between catchments of similar size. To do this, select “Catchments” in the left-hand sidebar

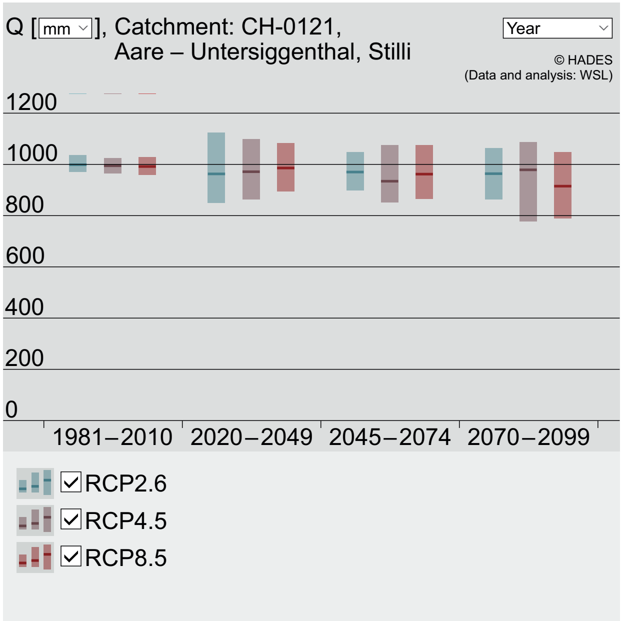

Figure 2. Aare–Untersiggenthal, Stilli: Reductions in annual discharge up to the end of the 21st century, according to the three emission scenarios RCP2.6, RCP4.5, and RCP8.5

under L02 and define the desired catchment size using the pull-down menu. Now the desired emission scenario, time period, etc. can be chosen in the right-hand sidebar. Figure 3 shows the relative changes in spring discharge towards the end of the 21st century under emission scenario RCP8.5 for catchments measuring approximately 3250 km^2. For fully inner-Alpine catchments (Rhône, Rhine), an increase in discharge is expected. This tendency cannot be observed for the catchments of the Aare or Reuss, as they have a larger share of low-lying areas and the changes to spring snowmelt are of relatively small importance.

6 Versions

Table 2. Versions

Version	Description
v1.0 (2020)	Version of the available data set: Version 1.0, September 2018.

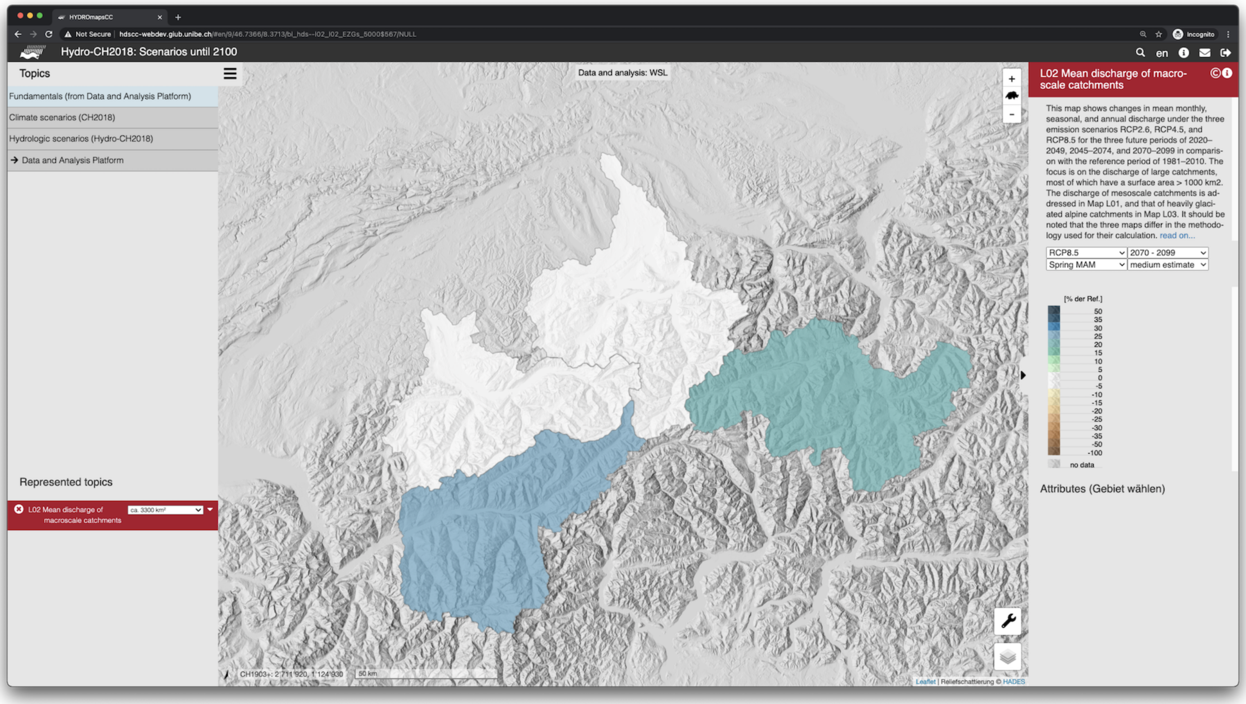

Figure 3. Relative change in spring discharge under emission scenario RCP 8.5. The map shows catchments measuring approximately 3250 km^2: Rhône– Sion; Aare–Bern, Schönau; Reuss–Mellingen; and Rhine–Domat/Ems (from the lower left and moving right).

References

[1] IPCC, Pachauri, R. and Meyer, L., eds. (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: IPCC.

[2] Michel, A., Brauchli, T., Lehning, M., Schaefli, B. and Huwald, H. (2020). Stream temperature and discharge evolution in Switzerland over the last 50 years: annual and seasonal behaviour. en. In: *Hydrology and Earth System Sciences* 24.1. `https://hess.copernicus.org/articles/24/115/2020/`, pp. 115–142. ISSN: 1607-7938. DOI: `10.5194/hess-24-115-2020`.

[3] Brunner, M. I. et al. (2019). Present and future water scarcity in Switzerland: Potential for alleviation through reservoirs and lakes. en. In: *Science of The Total Environment* 666. `https://linkinghub.elsevier.com/retrieve/pii/S0048969719306576`, pp. 1033–1047. ISSN: 00489697. DOI: `10.1016/j.scitotenv.2019.02.169`.

[4] Speich, M. J., Bernhard, L., Teuling, A. J. and Zappa, M. (2015). Application of bivariate mapping for hydrological classification and analysis of temporal change and scale effects in Switzerland. en. In: *Journal of Hydrology* 523. `https://linkinghub.elsevier.com/retrieve/pii/S0022169415001055`, pp. 804–821. ISSN: 00221694. DOI: `10.1016/j.jhydrol.2015.01.086`.

[5] Viviroli, D., Mittelbach, H., Gurtz, J. and Weingartner, R. (2009a). Continuous simulation for flood estimation in ungauged mesoscale catchments of Switzerland – Part II: Parameter regionalisation and flood estimation results. en. In: *Journal of Hydrology* 377.1-2. `https://linkinghub.elsevier.com/retrieve/pii/S0022169409005186`, pp. 208–225. ISSN: 00221694. DOI: `10.1016/j.jhydrol.2009.08.022`.

[6] Viviroli, D., Zappa, M., Schwanbeck, J., Gurtz, J. and Weingartner, R. (2009b). Continuous simulation for flood estimation in ungauged mesoscale catchments of Switzerland – Part I: Modelling framework and calibration results. en. In: *Journal of Hydrology* 377.1-2. `https://linkinghub.elsevier.com/retrieve/pii/S0022169409005174`, pp. 191–207. ISSN: 00221694. DOI: `10.1016/j.jhydrol.2009.08.023`.

[7] Köplin, N., Viviroli, D., Schädler, B. and Weingartner, R. (2010). How does climate change affect mesoscale catchments in Switzerland? – a framework for a comprehensive assessment. en. In: *Advances in Geosciences* 27. `https://adgeo.copernicus.org/articles/27/111/2010/`, pp. 111–119. ISSN: 1680-7359. DOI: `10.5194/adgeo-27-111-2010`.

[8] Bernhard, L. and Zappa, M. (2012). *Schlussbericht CCHydrologie: Teilprojekt WHH-CH-Hydro: Natürlicher Wasserhaushalt der Schweiz und ihrer bedeutendsten Grossein-*

zugsgebiete. Birmensdorf: Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft WSL.

[9] Jörg-Hess, S., Fundel, F., Jonas, T. and Zappa, M. (2014). Homogenisation of a gridded snow water equivalent climatology for Alpine terrain: methodology and applications. en. In: *The Cryosphere* 8.2. https://tc.copernicus.org/articles/8/471/2014/, pp. 471–485. ISSN: 1994-0424. DOI: 10.5194/tc-8-471-2014.

[10] Zekollari, H., Huss, M. and Farinotti, D. (2019). Modelling the future evolution of glaciers in the European Alps under the EURO-CORDEX RCM ensemble. en. In: *The Cryosphere* 13.4. https://tc.copernicus.org/articles/13/1125/2019/, pp. 1125–1146. ISSN: 1994-0424. DOI: 10.5194/tc-13-1125-2019.

[11] CH2018 (2018). *CH2018 – Climate Scenarios for Switzerland, Technical Report*. Zurich: National Centre for Climate Services.