Water Resour Manage (2012) 26:1231–1252
DOI 10.1007/s11269-011-9956-1

Variations in Discharge Volumes for Hydropower Generation in Switzerland

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Received: 29 March 2011 / Accepted: 5 December 2011 /

Abstract This study analyses the way climatic variations over the last century impacted the volumes of water available for hydropower production in Switzerland. The analysis relied on virtual intakes located all over Switzerland, which were assumed to be fed by water from mesoscale catchments. Intake capacities were designed using flow duration curves. The results show that the overall warming and increased winter precipitation observed in recent decades have led to more balanced discharge behaviours in rivers and more favourable conditions for electricity production than most periods in the past. In lower-altitude regions of Switzerland, the annual volume of water available for electricity production has not changed significantly; however, significantly more water is available in winters, while less is available during summers. In higher-altitude regions like the Swiss Alps, especially in glaciated catchment areas, significantly more water is available in both seasons; in other words, the annual volume of water available for hydropower production is significantly higher in these areas when compared to earlier periods. Comparison of these results with the actual amount of hydroelectricity produced over the same period reveals that hydrological variations cannot fully explain the variations in power production observed. Plant-specific analyses are needed of the impact of climatic changes on water management.

Keywords Alps · Climate change · Design discharge · Hydroelectric power · Flow duration curve · Switzerland

1 Introduction

Environmental measurements indicate that Switzerland's climate has undergone major changes. As in other parts of the world, Switzerland's mean air temperature increased over the last century, resulting in Alpine temperatures that are between 1.0 and 1.6°C warmer (Begert et al. 2005). The air temperature increase has been especially pronounced in winters

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and since the 1980s (Begert et al. 2005). Further, long-term trend analyses of mesoscale precipitation fields show that winters have become 20–30% wetter since 1901 (Schmidli et al. 2002) and that heavy precipitation events in winter and autumn have become more frequent (Schmidli and Frei 2005). The changes in air temperature and precipitation have also significantly influenced snow cover and glacier mass balances, both of which are important components of the runoff processes in many Swiss rivers. In particular, snow depth diminished in regions lying below 1300 m a.s.l. and the duration of closed snow cover decreased (Laternser and Schneebeli 2003; Scherrer et al. 2004). The rise in temperature led to greater melting of glaciers (Zemp et al. 2006; Huss et al. 2008a), further influencing the total runoff from glaciated catchments (Zappa and Kan 2007; Collins 2008; Pellicciotti et al. 2010). Many runoff series from Swiss mesoscale catchments display upward trends in annual runoff from 1931 to 2000 due to higher runoff amounts in winter, spring, and autumn (Birsan et al. 2005). Runoff behaviour in summer has been found to be inconsistent, displaying both upward and downward trends in mean runoff. Studies analysing changes in the water balance components of large-scale Swiss river systems over the last century ultimately found no significant changes in the amounts of annual runoff in northern Switzerland, but they found a significant decrease in annual runoff in the Ticino River in southern Switzerland (Belz et al. 2007; Hubacher and Schädler 2010; Hänggi and Weingartner 2011). So far, the increase in evapotranspiration resulting from higher air temperatures, changes in precipitation patterns, and/or changes in land use have barely impacted annual runoff in large-scale Swiss catchments, in particular because of compensating effects: a simultaneous increase in evapotranspiration and precipitation produces no effect on runoff ($R=P-ET$).

Overall, the studies indicate that the hydroclimatic conditions in Switzerland are inconsistently changing. However, most of the hydrological studies have analysed changes to naturally available runoff quantities in isolation; their results frequently do not address issues of water management. Thus, targeted analyses are needed in many sectors to determine the impact of climatic changes on water management.

Due to the paucity of information, the main aim of the present study was to analyse the impacts of observed climatic change on the design discharges and runoff volumes of hydropower plants in Switzerland. More than 50% of the electricity generated in Switzerland comes from hydropower plants (Swiss Federal Office of Energy [SFOE] 2010). To determine the energy potential of a hydropower plant, a design runoff volume (V_d) is set that defines the quantity of water available to produce electricity. The factor V_d mainly depends on the designed minimum and maximum discharge quantities (Q_{min} and Q_{max}) and the design discharge (Q_d) at which a desired turbine can produce energy. Normally, these three design discharges are extracted from flow duration curves (FDC) representing long-term hydrological conditions. Because of the variability of hydrological conditions, the actual quantity of water absorbed – or the effective runoff volume (V_a) available – can differ from the designed one, being higher in some years or lower in others.

In the present study, design discharges were set for virtual hydropower plants or intakes respectively, fed by water from specific mesoscale catchments in Switzerland. For the selected catchments, long-term runoff series were available that were essentially unaffected by human activities. This made them ideal for analysing possible climatic influences. The virtual hydropower plants were used to answer the following questions: have observed climatic changes significantly influenced the shape of the FDC? Has the effective runoff volume V_a available changed significantly? Has the duration of exceedance of designed minimum and maximum discharges (Q_{min} and Q_{max}) changed significantly? This duration equals the amount of time for which a hydropower plant is no longer able to produce energy.

All the virtual intakes were identically designed. This enabled direct comparison of all results from throughout Switzerland, across space and time. Results were rendered at annual and half-year temporal resolution. Runoff data are presented in Section 2. Methods are described in Section 3, including explanation of the set up of virtual designs. Results are presented in Section 4, followed by discussion and conclusions in Section 5 and Section 6 respectively.

2 Data

2.1 Runoff Data

To ensure appropriate time series for detection of climate change signatures, two main criteria were used when selecting gauging stations for analysis and as the basis for virtual intakes (cf. Kundzewicz and Robson 2004): (1) the absence of substantial influence on measurements due to the presence of large lakes or water withdrawals for hydropower generation or other water use purposes; (2) the availability of high-quality, complete daily measurements over a long period, from 1971 onward at minimum. In addition, the chosen basins had to be representative of the range of flow regime types in Switzerland (Weingartner and Aschwanden 1992). The gauging stations that were selected for the study are shown in Table 1 and Fig. 1. The stations are operated by the following entities: the Swiss Federal Office for the Environment (FOEN) (43 stations); cantonal authorities (6 stations), and the hydropower company Grande Dixence S.A. (2 stations). One of the catchment areas lies in Germany, but its river Wiese drains into Switzerland so it was also selected for the study.

The hydrological behaviour of rivers in Switzerland may be classified according to 16 different runoff regimes (Weingartner and Aschwanden 1992). With the exception of “nivo-glaciaire” (r5 in Table 1) and “pluvial méridional” (r16), regime types for which no long-term measurements are available, the runoff series examined in this study accounted for all Swiss runoff regime types:

The flows of regime types “glaciaire” (r1, r2) and “glacio-nival” (r3, r4) are strongly influenced by the melt of glaciers. They are typical of catchments located at high altitudes, above 2,000 ma.s.l., in the Swiss Alps. These regimes display high mean measures of monthly discharge in summers, particularly July and August when the melting of ice is most intense, yet display almost no runoff in winters when most precipitation falls as snow.

The “nival alpin” (r6) and “nival de transition” (r7) regimes display peaks in runoff between May and June. They are mainly influenced by snowmelt in the spring. Catchments with mean altitudes between 1,000 and 2,200 ma.s.l. belong to these regime types.

In lower-altitude parts of Switzerland, like those belonging to the Swiss Plateau, the runoff behaviour of streams is dominated by precipitation and evapotranspiration. The regime types in these areas are referred to as “pluvial” (r8, r9, r10). They exhibit balanced long-term mean regime, displaying only minor differences in monthly flows and sporadic anomalous flows for individual years.

Conditions similar to those of the Swiss Plateau may be found in northwestern Switzerland, in the Jura Mountains. However, the regime types in this region (r11, r12) are more heavily influenced by snow and specific hydrogeological conditions (karst).

In the southern part of the Swiss Alps lie regimes of the type “méridional” (r13, r14, r15). These regimes are characterised by a second discharge peak in autumn due to heavy precipitation events that usually occur at this time of year.

Table 1 Characteristics of the runoff series and basins studied. The runoff regimes were determined according to Weingartner and Aschwanden (1992)

	No.) Runoff regime	(No.) River Name-Location	Basin area [km^2]	Basin mean altitude [m a.s.l.]	Basin glaciation [%]	Time series	Operator
Swiss Alps	r1) a-glaciaire (ice fed, upper altitudes)	(1) Findelbach-Zermatt	23	3235	74.3	1962–2009	Grande Dixence S.A.
		(2) Gornera-Zermatt	83	3205	73.0	1969–2009	Grande Dixence S.A.
		(3) Lonza-Blatten	77.8	2630	36.5	1956–2009	FOEN
		(4) Massa-Blatten	195	2945	65.9	1931–2009	FOEN
		(5) Rhone-Gletsch	38.9	2719	52.2	1956–2009	FOEN
		(6) Rosegbach-Pontresina	66.5	2716	30.1	1954–2009	FOEN
	r2) b-glaciaire (ice fed, lower altitudes)	(7) Alpbach-Erstfeld	20.6	2200	27.7	1960–2009	FOEN
		(8) Simme-Oberried	35.7	2370	34.6	1944–2009	FOEN
	r3) a-glacio-nival (ice and snow fed, upper altitudes)	(9) Berninabach-Pontresina	107	2617	18.7	1954–2009	FOEN
		(10) Hinterrhein-Hinterrhein	53.7	2360	17.2	1945–2009	FOEN
		(11) Lütschine-Gsteig	379	2050	17.4	1920–2009	FOEN
		(12) W. Lütschine-Zweilütschinen	164	2170	17.6	1933–2009	FOEN
	r4) b-glacio-nival (ice and snow fed, lower altitudes)	(13) Dischmabach-Davos	43.3	2372	2.1	1963–2009	FOEN
		(14) Landquart-Klosters	112	2332	8.0	1933–2004	FOEN
	r6) nival alpin (snow fed)	(15) Allenbach-Adelboden	28.8	1856	-	1950–2009	FOEN
		(16) Grosstalbach-Isenthal	43.9	1820	9.3	1956–2009	FOEN
		(17) Ova Dal Fuorn-Zernez	55.3	2331	-	1960–2009	FOEN
		(18) Plessur-Chur	263	1850	-	1930–2009	FOEN
Swiss Plateau	r7) nival de transition (snow fed, transition to rain)	(19) Eubach-Euthal	8.95	1216	-	1960–2004	FOEN
		(20) Minster-Euthal	59.2	1351	-	1960–2009	FOEN
		(21) Simme-Oberwil	344	1640	3.7	1921–2009	FOEN
		(22) Sitter-Appenzell	74.2	1252	0.1	1912–2009	FOEN
		(23) Thur-Stein	84	1448	-	1963–2009	Ct. St. Gallen
	r8) nivo-pluvial préalpin (snow and rain fed)	(24) Emme-Emmenmatt	443	1070	-	1917–2009	FOEN
		(25) Kleine Emme-Littau	477	1050	-	1936–2009	FOEN
		(26) Sense-Thörishaus	352	1068	-	1928–2009	FOEN
		(27) Steinenbach-Kaltbrunn	19.1	1112	-	1968–2009	Ct. St. Gallen
		(28) Thur-Jonschwil	493	1030	-	1966–2009	FOEN
		(29) Urnäsch-Hundwil	64.5	1085	-	1961–2009	

Table 1 (continued)

	No.) Runoff regime	(No.) River Name-Location	Basin area [km^2]	Basin mean altitude [m a.s.l.]	Basin glaciation [%]	Time series	Operator
							Ct. Appenzell Ausserrhoden
	r9) pluvial supérieur (rain fed, upper altitudes)	(30) Glatt-Herisau	16.2	840	-	1961–2009	FOEN
		(31) Goldach-Goldach	49.8	833	-	1961–2009	FOEN
		(32) Gürbe-Belp	117	837	-	1922–2009	FOEN
		(33) Steinach-Steinach	24.2	710	-	1961–2009	Ct. St. Gallen
		(34) Töss-Wülflingen	260	688	-	1965–2009	Ct. Zurich
	r10) pluvial inférieur (rain fed, lower altitudes)	(35) Aach-Salmsach	48.5	480	-	1961–2009	FOEN
		(36) Bibere-Kerzers	50.1	540	-	1955–2007	Ct. Fribourg
		(37) Broye-Payerne	392	710	-	1920–2009	FOEN
		(38) Langeten-Huttwil	59.9	766	-	1966–2009	FOEN
		(39) Töss-Neftenbach	342	650	-	1921–2009	FOEN
		(40) Wiese-Basel	437	370	-	1933–2009	FOEN
Jura	r11) pluvial jurassien (rain fed, Jura)	(41) Ergolz-Liestal	261	590	-	1934–2009	FOEN
		(42) Mentue-Yvonand	105	679	-	1971–2009	FOEN
	r12) nivo-pluvial jurassien (snow and rain fed, Jura)	(43) Areuse-St-Sulpice	129	1081	-	1959–2009	FOEN
		(44) Birse-Moutier	183	930	-	1911–2009	FOEN
		(45) Orbe-Le Chenit	44.4	1220	-	1971–2009	FOEN
		(46) Suze-Sonceboz	150	1050	-	1961–2009	FOEN
Southern Alps	r13) nival méridional (snow fed, Southern Alps)	(47) Poschiavino-La Rösa	14.1	2283	0.4	1970–2009	FOEN
		(48) Riale Di Calneggia-Cavergno	24	1996	-	1967–2009	FOEN
	r14) nivo-pluvial méridional (snow and rain fed, Southern Alps)	(49) Riale Di Roggiasca-Roveredo	8.06	1711	-	1966–2009	FOEN
	r15) pluvio-nival méridional (rain and snow fed, Southern Alps)	(50) Breggia-Chiasso	47.4	927	-	1966–2009	FOEN
		(51) Cassarate-Pregassona	73.9	990	-	1962–2009	FOEN

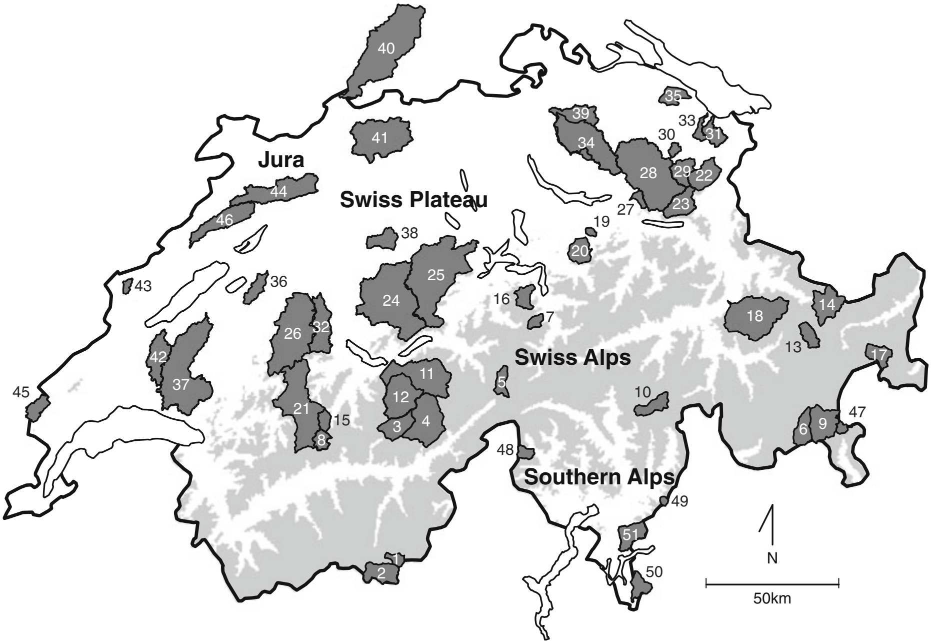


Fig. 1 Map of Switzerland showing the geographical locations of the basins of the virtual hydropower plants. Areas above 1500 ma.s.l. are shown in grey. The numbers match those of the "River Name-Location" listings in Table 1

2.2 Runoff Data Homogeneity

The selected runoff time series were tested regarding homogeneity using the Standard Normal Homogeneity Test (SNHT) for single shifts (Alexandersson 1986). The SNHT is designed to detect significant breakpoints in a standardised ratio (or difference) time series that has been calculated by comparing a candidate time series (in this case the selected runoff series) and a homogenous reference series. The ratio time series analysed in the present study were standardised by subtracting the mean and dividing by the standard deviation. The test statistic (T_0) was calculated according to

$$T_0 = \max_{1 \leq v \leq n-1} \left[v\bar{z}_1^2 + (n-v)\bar{z}_2^2 \right], \tag{1}$$

where n: sample size and $\bar{z}_1$, $\bar{z}_2$: arithmetic means of the sequences before and after a breakpoint. Corresponding to its maximum, v denotes the last point in time before a breakpoint. A breakpoint was considered significant if T_0 was above the critical level of 95%, in line with Khaliq and Ouarda (2007).

For the calculation of the ratio series, no known homogenous reference series were available. As a result, for each runoff series, several ratio series were calculated using neighbouring series that had a coefficient of correlation of at least 0.80 (Rapp 2000). The ratio series were then tested successively for multi-discontinuities according to Eq. 1 until significant breakpoints were no longer detected within a sub-series (Alexandersson 1995). A breakpoint in the candidate series was considered valid where at least two or more neighbouring series indicated a breakpoint in the same year (Fig. 2).

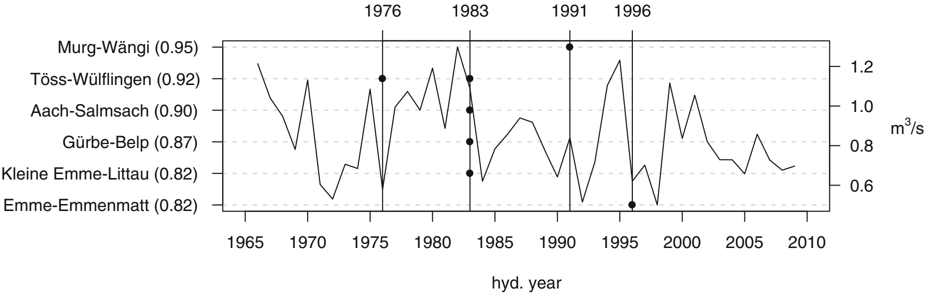


Fig. 2 Inhomogeneity of the runoff series from the Eulach river in Winterthur (1966–2009). The reference stations used for the SNHT are ordered from top to bottom according to decreasing correlation values (in brackets). Four neighbouring stations indicate that the Eulach runoff series had a significant breakpoint in 1983 (dots)

The SNHT was applied to mean annual runoff time series (hydrological years measured from 1 October of 1 year to 30 September of the next year), since signs of inhomogeneity are more pronounced and distinguishable in annual series when compared to monthly or daily time series (Rapp 2000). Out of the 57 initially selected time series, six displayed significant discontinuities: Chamuerabach La Punt, Ova da Cluozza Zernez, Eulach Winterthur, Wildbach Wetzikon, Murg Wängi, and Birs Münchenstein. They were eliminated from the original data sample because homogenisation of the affected series was beyond the scope of the present study.

3 Method

3.1 General Remarks on the Definition of the Design Volumes and Design Discharges

The design volume V_d is mainly used to determine the energy potential of hydropower plants. It expresses the mean volume of water that can be expected to be available for production of energy. It is normally defined using long-term discharge data. V_d may be derived from FDC, as it represents a portion of the area under the curve (Fig. 3).

The FDC shows the percentage of time that runoff from a river is likely to equal or exceed some specified discharge of interest. For example, the discharge Q_{95} is reached or exceeded 95% of the time. The method of deriving V_d from the FDC is often used when initially determining the energy potential of a hydropower plant, especially run-of-river plants and smaller plants. In most cases V_d is defined in accordance with the following two parameters (BFKF 1995):

1. The design discharge Q_d represents the maximum runoff quantity that can be used/absorbed by a plant/intake. Runoff values greater than Q_d cannot be completely absorbed and thus overflow the intake.
2. A minimum quantity of water, Q_{min}, is left because the minimum turbine head is reached, or has to be left for irrigation, water supply, ecological flow, fish passage facilities or other purposes. Discharges less than Q_{min} cannot be used by the plant.

A third parameter Q_{max} was also applied in order analyse changes in flood occurrence: if runoff exceeded the Q_{max}, it was posited that the plant or intake would have to cease operating for a certain period as high bed load rates could damage plant infrastructure. In

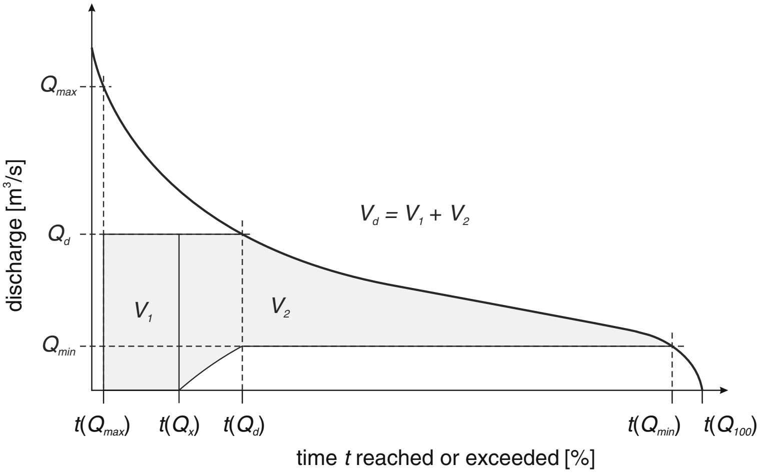


Fig. 3 Long-term mean FDC. Q_{max}: maximum discharge [m^3/s]; Q_d: design discharge [m^3/s]; Q_{min}: minimum discharge [m^3/s]; and V_d: design volume [m^3]

such cases, the plant would not use any water. This parameter normally is not used when defining the V_d because it is assumed that discharges higher than Q_d will be spilled without damaging plant infrastructure.

Having set Q_d, Q_{max}, and Q_{min}, the design volume V_d can be calculated according to

$$V_d = V_1 + V_2, \tag{2}$$

$$V_1 = Q_d \cdot (t(Q_x) - t(Q_{\max})),$$

$$V_2 = \sum_{i=t(Q_x)}^{t(Q_{\min})} (Q_i - Q_{\min})$$

In Eq. 2, V_1 and V_2 represent areas under the FDC (cf. Fig. 3); V_d: design volume; t: time of exceedance; and $t(Q_x)$: time of exceedance where Q_x-Q_d=Q_{min}.

The design values of Q_d, Q_{max}, and Q_{min} depend on the desired operation or purpose of the hydropower plant (BFKF 1995). For a hydropower plant operating in an isolated network – where it is the only source of energy and must consistently produce electricity throughout the year – the approximate values are $Q_d \leq Q_{70}$. For a hydropower plant in parallel operation – where it is part of an existing network of other plants and is used to maximise energy production – values for Q_d between Q_{15} and Q_{25} are used. As mentioned, Q_{max} and Q_{min} depend on the infrastructure and the general conditions of the project.

Various other parameters influence the productivity of hydropower plants in addition to the design values discussed above, such as the specification of the hydraulic head or the choice of the turbine and generator (BFKF 1995). However, these parameters were not considered in this study since they are not directly affected by climatic changes. The impact of climate change, such as hotter summers, on the energy market was also excluded.

3.2 Definition of the Virtual Design Volumes and Discharges in this Study

The selected runoff series were used to determine the design volumes V_d for virtual hydropower plants or intakes respectively. To enable comparison, the thresholds Q_d, Q_{max}, and Q_{min} were held constant across all the catchments analysed. The design discharge Q_d was set to Q_{25}, that is, the discharge value that is reached or exceeded 25% of the time. The Q_{max} was set to Q_2 and the Q_{min} was set to Q_{95}. The effect of the choice of design values on V_d was investigated separately and is also presented below. The respective values of the three thresholds were calculated using mean FDCs from 1995–2009, viewed as representing "today's climate". Hydrological years beginning 1 October of one year and ending 30 September of the next year were used for the entire study, with winters defined as running from October to March and summers defined as running from April to September. The mean FDCs were calculated by sorting all daily mean discharge values of the reference period in descending order.

3.3 Sensitivity Analysis of V_d Based on the Choice of Design Discharges

The influence of the choice of Q_d and Q_{min} on V_d was investigated by analysing changes in the ratios between designed discharge volumes V_d and total discharge volumes V_n. The sensitivities were calculated for different Q_d, varying between Q_{15} and Q_{85}, and different Q_{min}, varying between Q_{90} and Q_{100}. Since the parameter Q_{max} has only a marginal effect on V_d (cf. Eq. 2), it was held constant at Q_2 for all calculations. A high dispersion of ratios indicates a high sensitivity of the corresponding runoff series regarding the choice of the design discharges, a low dispersion vice versa. The sensitivity analysis was performed for all available mean FDCs for the period 1995–2009.

3.4 Analysis of Changes in the Flow Duration Curves

The water volumes available to the virtual hydropower plants were analysed based on the FDCs. The mean FDCs of the equal-length periods 1935–1949, 1950–1964, 1965–1979, and 1980–1994 were compared with the FDC of the reference period 1995–2009 to detect anomalies (Fig. 4). A bootstrap analysis was used to test if any differences (anomalies) between the individual FDCs were statistically significant (Efron and Tibshirani 1993): 1,000 samples were generated from the reference period, each of them containing 15 randomly extracted years (sampling with replacement). The mean FDCs were then calculated from these samples. The resulting distribution of mean FDCs was used to define the lower and upper bounds (2.5–97.5%) of the confidence bounds for the reference period 1995–2009.

3.5 Analysis of Changes in the Natural Discharge Volumes Available for Hydropower Generation

V_d is the available runoff volume, which is based on the long-term mean FDC. The yearly effective (or absorbed) runoff volume V_a will differ from V_d, being higher in some years and lower in others. In addition to this parameter, other parameters were calculated that characterise individual years and enable comparison, including: the annual number of days that the designed maximum discharge Q_{max} was exceeded, and the annual number of days that the designed minimum discharge Q_{min} was not met. Total annual discharge volumes V_n were

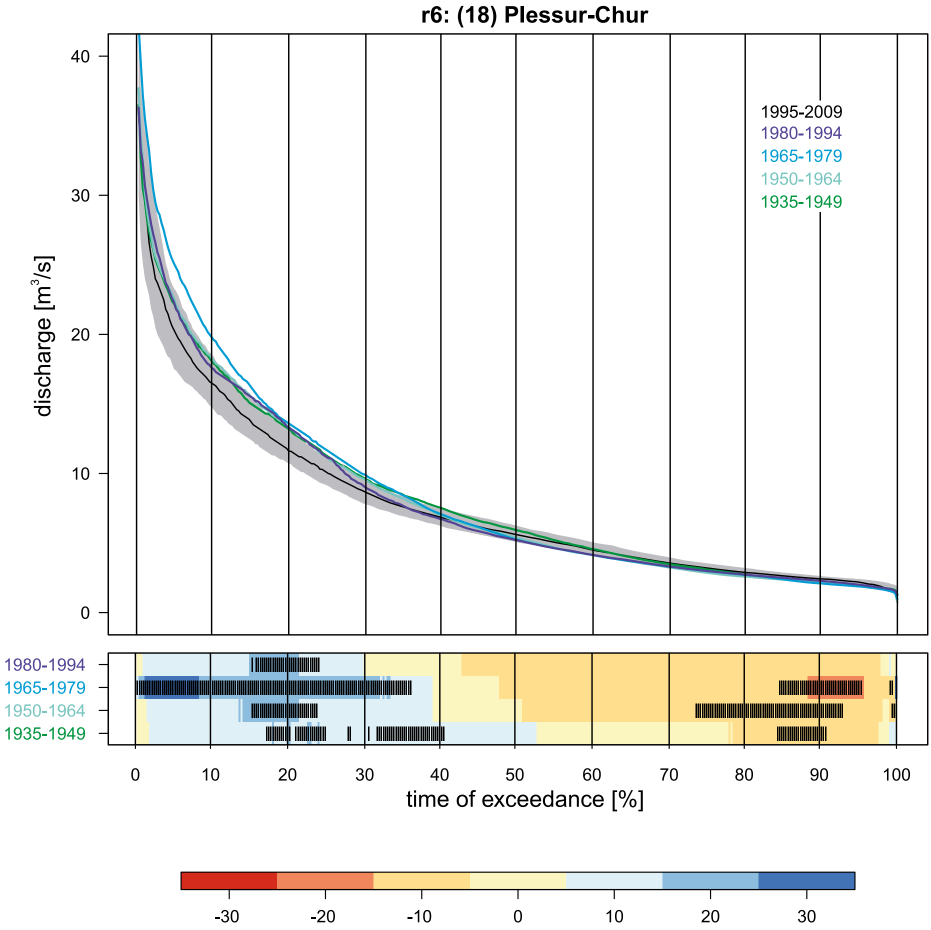


Fig. 4 Top: mean FDCs of different periods for the river Plessur at Chur. The grey area indicates the 95% confidence interval of the reference period 1995–2009. Bottom: FDC anomalies from 1995–2009 (colour scale, [%]). Q-values differing significantly from those of the reference period are shaded

also calculated for the sake of comparison. The resulting time series of these parameters were smoothed using a 15-year moving average. Again, the smoothed values were compared with the mean conditions in the reference period 1995–2009 to detect anomalies. As described above, a bootstrap analysis was used to test the significance of detected anomalies. First, 1,000 samples were randomly generated from the reference period. Next, the mean was calculated from each sample. The distribution of means from these samples was used to define the lower and upper bounds (2.5–97.5%) of the confidence interval for the reference period 1995–2009.

The variations in runoff volumes were also analysed separately for winters (October to March) and summers (April to September). Thus, for each year, the contribution of winter and summer discharge volumes were separately analysed with respect to the total annual discharge volumes, and the resulting time series were analysed as described above.

4 Results

4.1 Sensitivity of V_d based on the Choice of Design Discharges

The sensitivity of V_d to the choice of the design discharges Q_d and Q_{min} is shown in Fig. 5. A high dispersion of the ratio between the designed discharge volume V_d and the total discharge volume V_n indicates a high sensitivity of the corresponding runoff series to the choice of design discharges, a low dispersion vice versa.

The results show a high sensitivity of V_d to the choice of Q_d for runoff series from glaciated catchments, namely the runoff regimes (r1) a-glaciaire, (r2) b-glaciaire, (r3) a-glacio-nival, and (r4) b-glacio-nival. Depending on the choice of Q_d, the ratios vary between 0.0 and 0.8.

The design volumes for runoff series from catchments representing snow-dominated regimes (r6 and r7) are less sensitive to the choice of Q_d, but display a relatively high sensitivity to the choice of Q_{min}. This is also true of runoff regimes dominated by rain (r8, r9, and r10). Notable for these types of runoff regimes is that Q_{min} variations between Q_{95} and Q_{100} (Fig. 5: upper light-grey bars) have a much greater effect on the design volume than do variations between Q_{90} and Q_{95} (Fig. 5: lower light-grey bars). This may be seen in greater detail in Fig. 6 where the sensitivity of V_d to changes to both Q_d and Q_{min} simultaneously is shown for three selected runoff series. The time series represent runoff regimes dominated by glacier melt (r2), snowmelt (r7), and precipitation (r10).

The choice of Q_{min} in glaciated catchments has almost no effect on the design volume. By contrast, the design volume's sensitivity to the choice of Q_{min} is high in catchments dominated by snowmelt and, especially, in those dominated by precipitation.

4.2 Changes in the Flow Duration Curves

In Fig. 7, the mean FDCs of the time periods 1935–1949, 1950–1964, 1965–1979, and 1980–1994 are compared with the FDC of the reference period 1995–2009.

Relatively few runoff series were available to analyse FDC anomalies for the periods 1935–1949 and 1950–1964: the time series available generally indicated that flows were lower in these earlier periods compared with today. With the exception of very high and low flows in certain time series, most of the differences were not significant.

The results for the period 1965–1979, for which a substantial amount of data is available, show that the flows in Alpine catchments were significantly lower in that span of time when

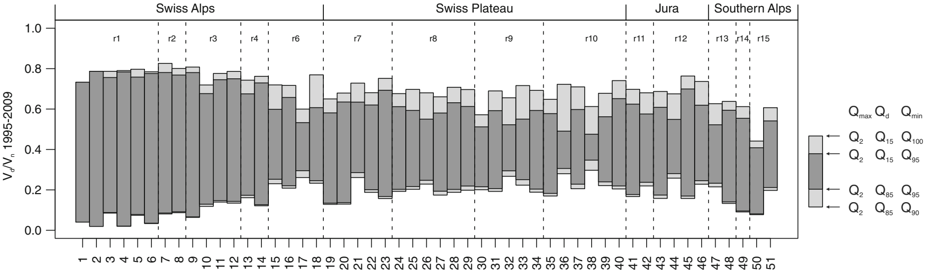


Fig. 5 Station-wise ratio areas V_d/V_n for different design discharge values: the dark grey bars indicate the area of ratios for Q_d varying from Q_{15} (upper bound of the bar) to Q_{85} (lower bound); the light grey bars indicate the additional area of ratios for Q_{min} varying from Q_{90} to Q_{100}. The Q_{max} is set at Q_2. The station and regime numbers correspond to Table 1

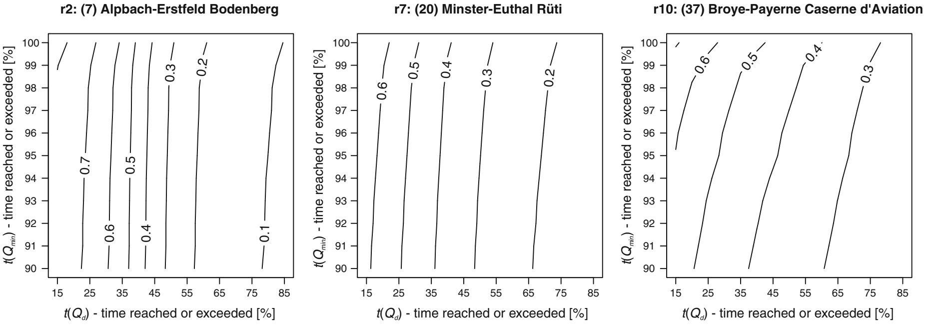


Fig. 6 Ratios V_d/V_n (surface area) resulting from changes to both Q_d (x-axis; Q_{15}–Q_{85}) and Q_{min} (y-axis; Q_{90}–Q_{100}) simultaneously: (r2) b-glaciaire (ice fed); (r7) nival de transition (snow fed); (r10) pluvial inférieur (rain fed)

compared to flows in the reference period 1995–2009. This is particularly true for the FDCs of glaciated river systems (regime types r1, r2, r3, and r4). It is also valid for the snowmelt-dominated regimes r6 and the pre-alpine type r7; however, in these cases, the large discharges from Q_1 to Q_{40} are significantly higher when compared with the conditions of the reference period. The FDCs of these rivers are therefore more balanced today. Only a few runoff series from the rain-dominated Swiss Plateau (r8, r9, r10) and from the Jura (r11, r12) display significant differences. The only time series representative for the flow conditions in the Southern part of the Alps indicate significantly higher Q-values in the past.

In general, the differences obtained by comparing the period 1980–1994 to the reference period are less pronounced than those obtained by comparing the period 1965–1979 to the reference period.

4.3 Variations in Annual V_n and V_a

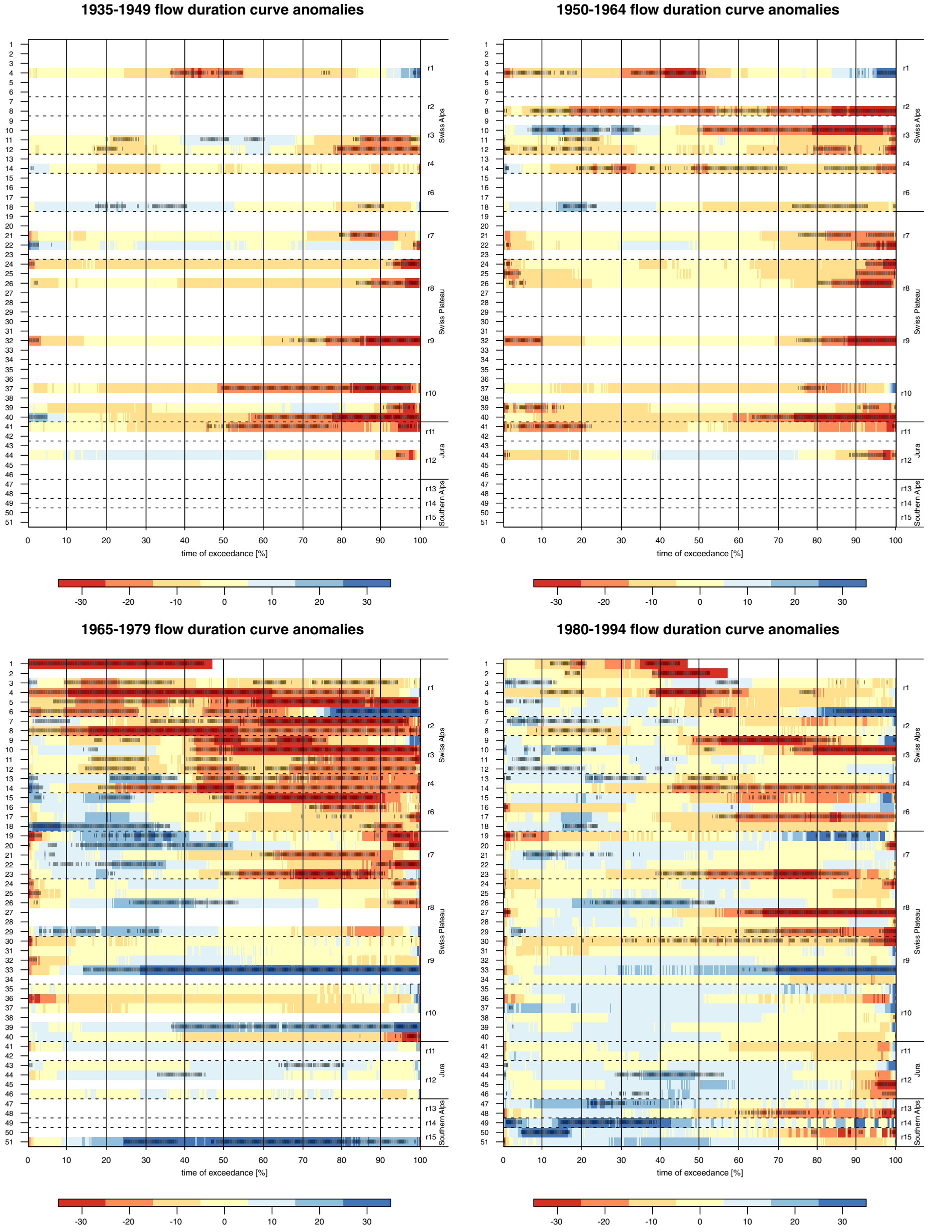
Figure 8 shows the 15-year moving average of anomalies in total annual volume V_n and in effective volume V_a – relevant for hydropower generation – when compared to the reference period 1995–2009.

The pattern of variations in total annual runoff volume compared to the available runoff volume is very similar over the last century. In comparison with the reference period 1995–2009, the catchments for which very early data are available indicate slightly wetter conditions around the period 1926–1940. Afterwards, quite a few time series indicate significantly lower runoff volumes. This subsequent drier phase extends until the period 1951–1960. From 1971–1985 to 1981–1995, some time series indicate higher runoff volumes, particularly in the Southern Alps. Particularly worth of note are the variations in runoff volumes belonging to the most glaciated catchments (regime numbers r1–r4): they display significantly lower runoff volumes for most of the earlier periods analysed when compared with the reference period. This is especially true of the variations in V_a.

4.4 Variations in Winter and Summer V_n and V_a

Figure 9 shows the 15-year moving average of anomalies in V_n and V_a for winter and summer, when compared to the reference period 1995–2009.

Like the annual volumes, the variations in V_{n_winter} compared to V_{a_winter} are very similar – they display almost the same patterns of change: for most of the last century, winter runoff


1935-1949 flow duration curve anomalies

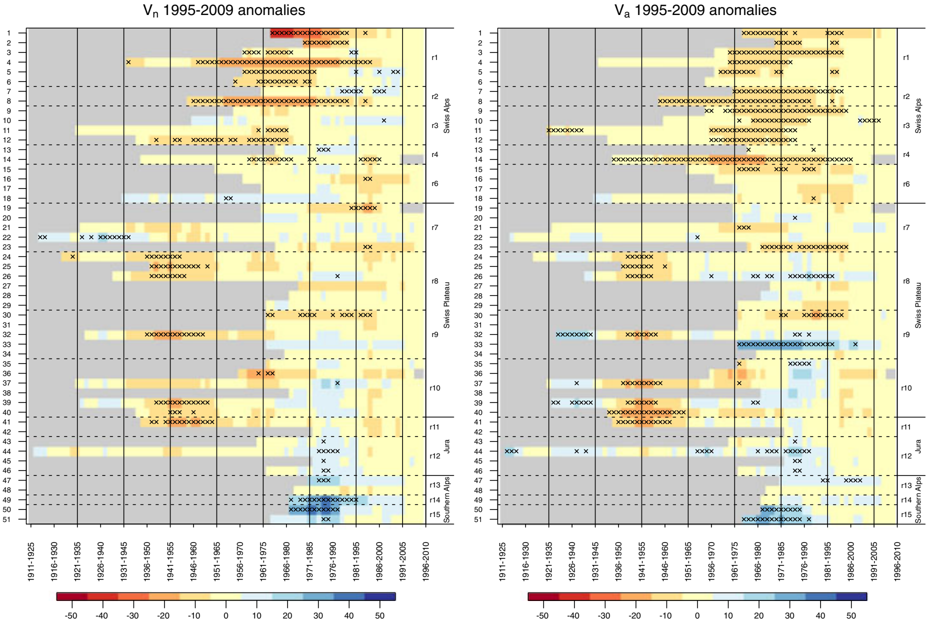
1950-1964 flow duration curve anomalies

1965-1979 flow duration curve anomalies

1980-1994 flow duration curve anomalies

Fig. 7 FDC anomalies (colour scale, [%]) for the periods 1935–1949, 1950–1964, 1965–1979, and 1980–1994 when compared to the reference period 1995–2009. Q-values differing significantly from those of the reference period 1995–2009 are shaded ($p \leq 0.05$). White areas indicate no data. The station and regime numbers correspond to those in Table 1

volumes V_{n_winter} and V_{a_winter} were lower than today in the majority of catchments. Especially in the periods 1956–1970 and 1966–1980, many runoff series display significant differences compared with today. Following these periods, runoff volumes suddenly increased, making more water available for hydropower production (though not significant compared with the



V_n 1995-2009 anomalies

V_a 1995-2009 anomalies

Fig. 8 15-year moving average of anomalies (colour scale, [%]) in total annual volume V_n and in effective volume V_a – relevant for hydropower generation – from selected Swiss catchments, when compared to the reference period 1995–2009. Periods differing significantly from the reference period 1995–2009 are indicated with crosses ($p \leq 0.05$). Grey areas indicate no data. Station and regime correspond to those in Table 1

conditions in 1995–2009). The precipitation-dominated regimes r9 and r10 in the Swiss Plateau show this type of increase even earlier, beginning from 1971–1985 onward. While the changes in V_{n_winter} versus V_{a_winter} are very similar, those observed in V_{a_winter} are more pronounced. This is particularly true of the volumes from glaciated catchments of regime types r2, r3, and r4: today significantly more water is available in the six months of winter compared with previous years.

Regarding summers, the variations in V_{n_summer} versus V_{a_summer} are similar once again, though differences in V_{a_summer} are much more evident: when compared with the reference period, almost all runoff series representing the conditions of the Swiss Plateau had significantly higher summer discharge volumes available for hydropower production in the periods from 1911–1925 to 1931–1945 and from 1951–1965 to 1981–1995. This is also true of the rivers belonging to the Jura and the Southern Alps. In contrast to this, the runoff regimes representing glaciated catchments r1, r2, r3, and r4 delivered significantly less water in the summer during most periods in the past.

To analyse the influence of both variations in V_{a_winter} and variations in V_{a_summer} on annual available runoff volumes V_a, changes in the ratios V_{a_winter}/V_a and V_{a_summer}/V_a over time were investigated (Fig. 10). The ratios are given relative to those of the reference period 1995–2009.

For most periods and the majority of runoff series analysed, the proportion of V_{a_winter} out of the total available runoff volume V_a was lower in the past when compared with today, and little variation is visible between successive periods. With the exception of the runoff series corresponding to the runoff regimes (r1) a-glaciaire, (r9) pluvial supérieur, (r10) pluvial inférieur, and (r11) pluvial jurassien, the ratios in most series were significantly lower within

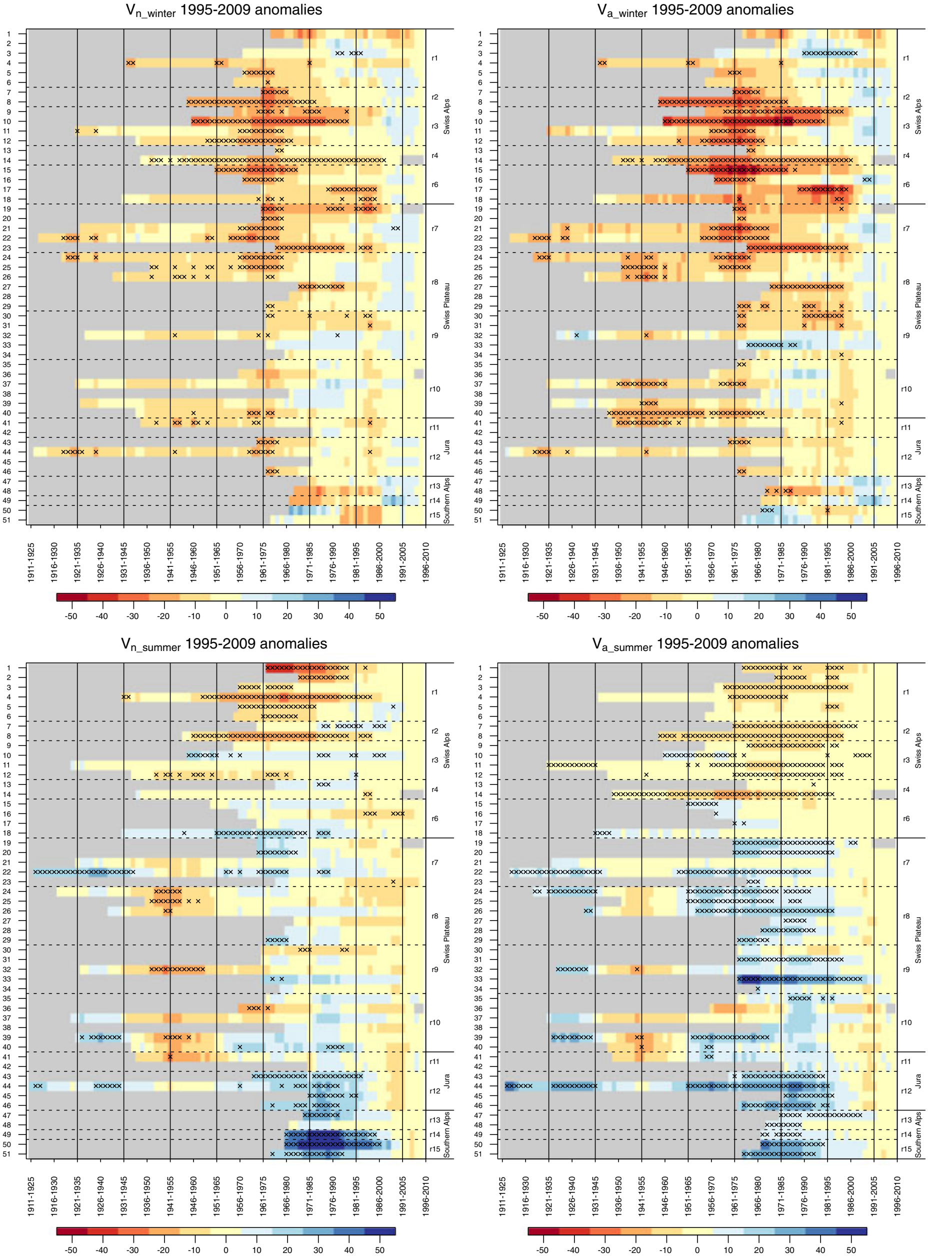


Fig. 9 Similar to Fig. 8, but for winter (October to March; upper plots) and summer (April to September; lower plots)

the periods 1911–1925 to 1931–1945 and 1946–1960 to 1986–2000, when compared to the reference period. Beginning in the period 1987–2001, the majority of ratios suddenly became higher than those of the reference period 1995–2009. However, the higher

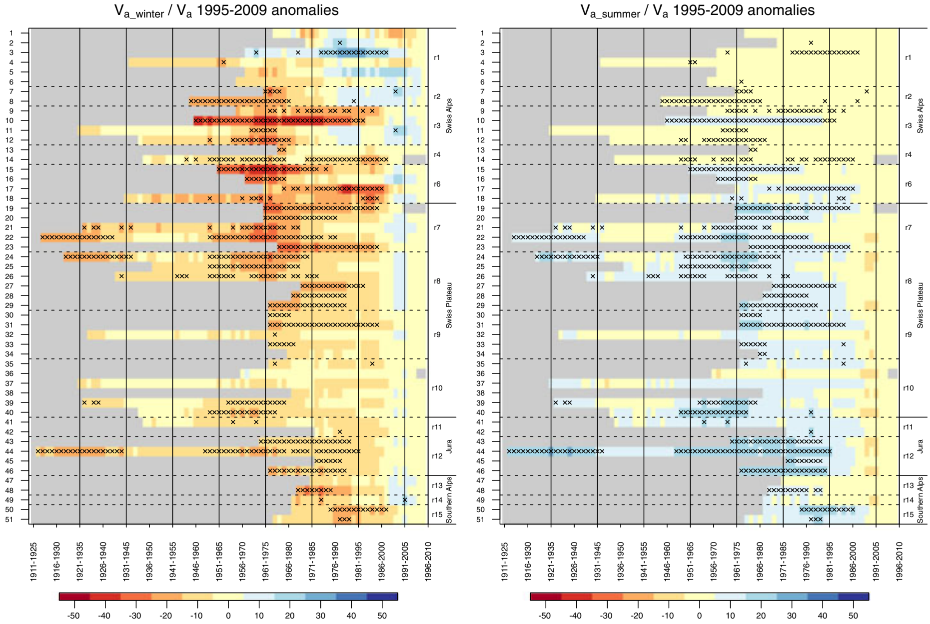


Fig. 10 15-year moving average anomalies (colour scale, [%]) of the ratios V_{a_winter}/V_a and V_{a_summer}/V_a from selected Swiss catchments, when compared to the reference period 1995–2009. Periods differing significantly from the reference period 1995–2009 are indicated with crosses ($p \leq 0.05$). Grey areas indicate no data. Station and regime numbers correspond to those in Table 1

proportions of winter discharges (out of total available volumes) found from the period 1987–2001 on are not significant.

The variations in the ratios of V_{a_summer}/V_a are the exact reverse of those observed for V_{a_winter}: most series had higher available water volumes in previous summers, especially the regime types cited directly above within the periods 1911–1925 to 1931–1945 and 1946–1960 to 1986–2000. Once again, a sharp change in the ratio series may be observed beginning in 1987–2001, suggesting that the earlier pattern of differing winter and summer runoffs abruptly switched to a more balanced pattern of discharge between the two seasons. Further, similar to the winter ratios described above, little variation is visible between the summer ratio series of successive periods over the last century. This points to stable proportions of $V_{a\_winter}/V_{a\_summer}$ in the past. Exceptions include those runoff series influenced by glacier melt and regime types r1, r2, r3, and r4, as their contribution of V_{a_summer} to total available runoff volume V_a was not higher in the past when compared with the conditions of the reference period 1995–2009.

4.5 Variations in the Number of Days Exceeding Q_{max} or Falling Below Q_{min}

For every year, the number of days exceeding the designed maximum discharge Q_{max} (Q_2=2% of the time or 7 days), and the number of days falling below the minimum discharge Q_{min} (Q_{95}, 347 days) were computed. During such times of exceedance of Q_{max} or days falling short of the Q_{min}, the virtual hyropower plants would have been forced to cease operating. The yearly time series were smoothed using a 15-year moving average. The results are presented in Fig. 11.

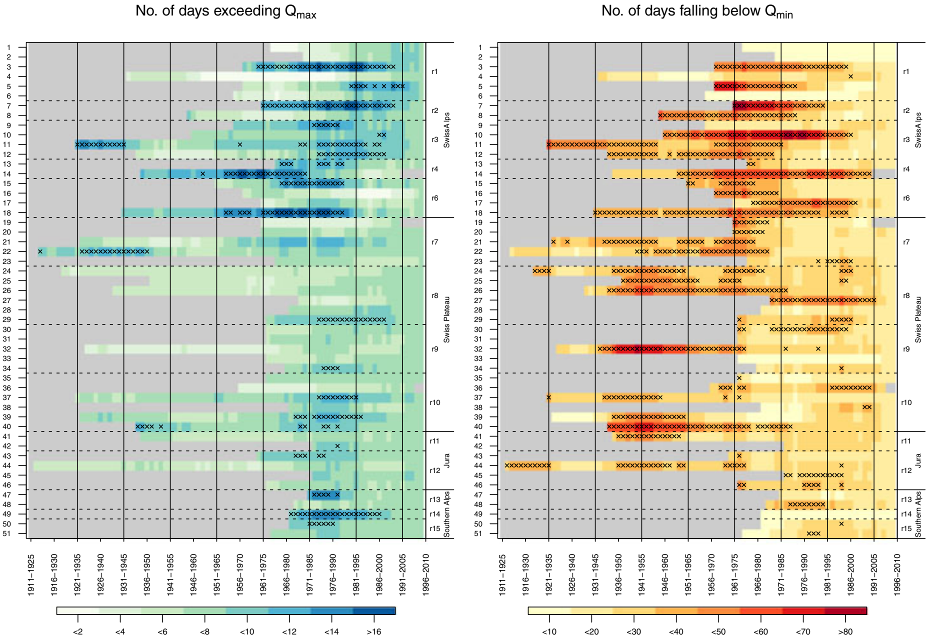


Fig. 11 15-year moving average of annual number of days exceeding Q_{max} or falling below Q_{min} from selected Swiss catchments (colour scale, [d]), when compared to the reference period 1995–2009. Periods differing significantly from the reference period 1995–2009 are indicated with crosses ($p \leq 0.05$). Grey areas indicate no data. Station and regime numbers correspond to those in Table 1

Above all, the regime types of the Swiss Alps (r1 to r6) displayed significantly more days during which the designed discharges Q_{max} were exceeded. This is particularly true of the periods 1966–1980 to 1981–1995. Also in these periods, the rain-dominated regimes r10 and those of the Southern Alps (r13 to r15) had more days during which Q_{max} was exceeded. The longest mean time of exceedance calculated was 17 days. The other periods and regime types showed few significant differences compared to the conditions of 1995–2009.

Differences in the number of days falling below Q_{min} are much more evident than those of days exceeding Q_{max}: for nearly all runoff series and the periods 1931–1945 to 1963–1977, significantly more days fell below the designed discharge Q_{min}. For many time series representing conditions in the Swiss Alps (r1 to r6), significantly lower flows are visible in the periods prior to 1986–2000.

In summary, the changes observed – indicating a decrease in the number of days where Q_{max} is exceeded and a decrease in the number of days where Q_{min} is not met – point to more favourable hydrological conditions for hydropower generation in 1995–2009 when compared to previous periods.

5 Discussion

The analyses of annual available runoff volumes V_a for hydropower production show that the total amounts have changed significantly in only a few regions of Switzerland. For example, significantly more water is available today in rivers that are highly influenced by the melt of glaciers. Overall, the changes observed in seasonal discharge behaviour are much more pronounced, and indicate more balanced river discharge behaviour today when compared to previous conditions. In addition, the differences between the high and low flows have gotten smaller. The change in the seasonality of discharge volumes appears to have occurred abruptly and can be seen from the mid-1980s onward. When compared with the conditions of the reference period 1995–2009, rivers in the Southern Alps, the Swiss Plateau, and the Jura Mountains had more water available for hydropower production in previous summers (from 1951 to 1995) and less water available in previous winters. This is particularly evident in the runoff series of snowmelt-dominated catchments in the Southern Alps. By contrast, significantly more water is available for hydropower production in both seasons today in the glaciated catchments of the Swiss Alps, resulting in higher annual volumes in those catchments.

Birsan et al. (2005) also found significant increasing trends in low flows (discharges in between Q_{80} and Q_{100}) in winter, spring, and autumn during three periods 1931–2000, 1961–2000, and 1971–2000. The findings of the present study are consistent with climatic changes observed using other hydroclimatic parameters: abrupt increases have been found in winter air temperatures from the 1980s onward (Begert et al. 2005). The warmer winters have given rise to significant changes in runoff behaviour, since in lower-altitude regions precipitation directly drains into the rivers rather than being retained as snow. Particularly in regions lying below 1300 ma.s.l. – the mean altitude of Switzerland – Scherrer et al. (2004) have found evidence of significant reductions to the depth of snow layers. The catchments of snow-fed rivers corresponding to regime types (r6) nival alpin and (r7) nival de transition are located at about this altitude. Further, winters have become 20–30% wetter since 1901 (Schmidli et al. 2002). However, according to the present results, no changes have occurred in the winter runoff series belonging to regime type (r1) a-glaciaire – located at very high altitudes (catchments with mean altitudes higher than 2400 ma.s.l.) – and glaciated catchments. Overall warming in these regions has not significantly influenced the state of precipitation or the appearance of the snow cover. Regarding the Swiss Alps, Beniston (1997) found that even at altitudes as low as 1750 ma.s.l. snow always exists throughout the winter season in both warm and cold winter conditions. In these regions, the increased runoff volumes are mainly the result of increased glacier melt rates during late spring and summer (Zemp et al. 2006; Zappa and Kan 2007; Huss et al. 2008b; Collins 2008; Pellicciotti et al. 2010).

From a theoretical perspective, the observed climatic changes should have given rise to higher volumes of water available for hydropower production and fewer production stops due to spillages or shortfalls. As a result, one would expect greater production of electricity in recent years when compared to earlier periods. Further, one would expect higher production rates in recent winters and lower production rates in recent summers. To test these expectations, which were based on hydrological findings, the actual electricity production of Swiss hydropower plants was analysed. The Swiss Federal Office of Energy (SFOE) routinely publishes the total annual production of Swiss hydropower plants. In addition, the SFOE estimates the mean potential production of all hydropower plants by taking into account the installed electrical power and a long-term mean of the hydrological conditions in Switzerland (SFOE 2010). As such, their estimation is mainly based on the building or modification of hydropower plants rather than on changes in the hydrological conditions. One might assume that the difference between the observed electricity production and the trend in the installed electrical power would reflect changes in hydrology only (Fig. 12, detrended observed production). However, the authors note that other factors, such as the electricity market, influence the development of production.

The SFOE data of annual observed production rates indicate a slight positive trend, which is in concordance with the results of the present analyses in terms of annual available

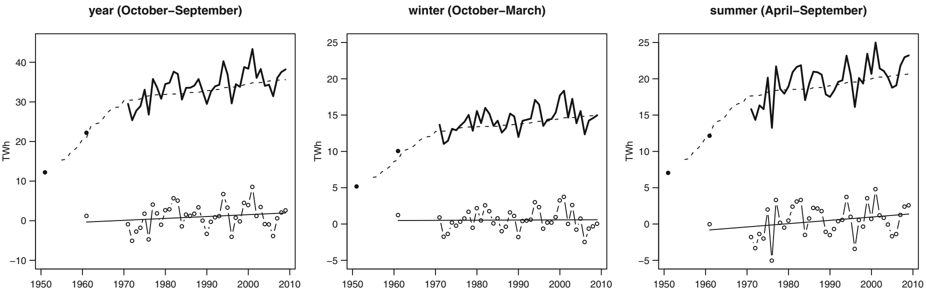


Fig. 12 Annual and seasonal electricity production [TWh] of Swiss hydropower plants 1950–2009. Solid line: observed production; dashed line: mean potential production; line with dots: detrended observed production (by using the mean potential production); and straight line: trend estimation of the detrended observed production. Data source: SFOE (2010)

discharge volumes for hydropower generation. However, in contrast to the present study's findings regarding changes in Switzerland's hydrological conditions, the observed electricity production remained stable in winters and even increased in summers. This differs from the results of the present study with respect to both seasons, as increasing volumes of usable water were mainly found in winters while decreasing volumes of usable water were mainly found in summers.

On the one hand, these contradictions – particularly the observed production increase in summers – may be explained by general characteristics of hydropower production in Switzerland: depending on the year, around 60–70% of the total electricity currently produced by hydropower comes from plants situated in the Swiss Alps (including the Southern Alps), while only 20–30% of the electricity comes from plants situated in regions of the Swiss Plateau and the Jura Mountains (SFOE 2010). In addition to having more water available, the Alpine regions are able to produce more electricity with the same amount of water, since the elevation-dependent energy potential is much greater in such areas. Thus, changes in the hydrological conditions of Alpine rivers have a much greater impact on Switzerland's total electricity production than hydrological changes in other regions. In addition, rivers draining form Alpine regions have a remarkable long-range effect on large-scale river systems in the lowlands (Viviroli and Weingartner 2004). Hänggi and Weingartner (2011) have shown that summer runoff in Basel's Upper Rhine River, which drains more than 67% of the total area of Switzerland and feeds major river power plants, did not change significantly since 1808. Consequently, the observed overall increase in summer electricity production is consistent with the increase in water volumes available for hydropower production found for rivers of the Swiss Alps. The decreases in available water found in mesoscale catchments situated in other parts of the country did not diminish actual summer electricity production.

On the other hand, market forces may also have contributed to the observed increase in summer electricity production, since generation of electricity is more profitable today. In earlier periods, most of the filling curves of storage hydropower plants show that filling began by May and ended in September (Fig. 13). Starting in September and continuing until April, the reservoirs were emptied to produce of electricity during the winter (cf. Weingartner and Pfister 2007). However, the five-year mean filling curve for the most recent period 2005–2009 shows a shift towards starting the emptying of reservoirs earlier than September – even in cases where reservoirs are not completely filled – likely due to the increased profitability of power generation in summer. Further, the previous two filling curves, for the periods 2000–

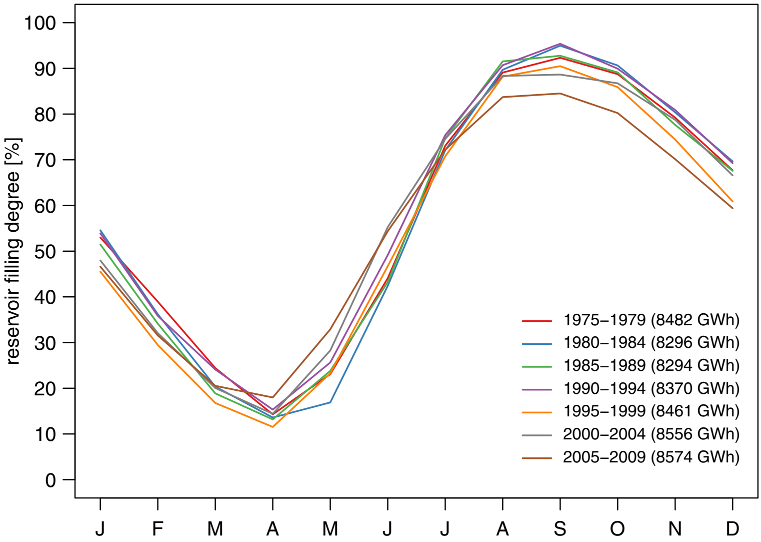


Fig. 13 Filling curves [%] of Swiss storage hydropower plants 1975–2009 (means over 5 years; mean total storage capacity of the period is given in brackets). Data source: SFOE (2010)

2004 and 2005–2009, show earlier, faster filling of reservoirs in May, pointing to an earlier start to the snowmelt season. Currently, around 10% more water is registered in reservoirs in the month of June than in that month in the 1980s.

Further, the overall stability of the filling curves also helps explain the observed stability of electricity production in winter. No sharp variations are visible in the filling curves of successive earlier periods. Thus, the storage capacities of Swiss hydropower plant reservoirs appear less sensitive to hydro-climatic variability, that is, they are moderately dimensioned. As a result, the production of electricity in winter – which currently depends primarily on the water volumes stored in reservoirs (SFOE 2010) – is not necessarily impacted by the significant increase in absorbed winter runoff volumes found in the present analyses. In addition, in absolute terms, the recent significant increase in the winter runoff of Alpine regions is of minor importance: in Switzerland, peak discharges still occur in the summer months. Figure 12 shows that in general more electricity is produced in summer than in winter (depending on the year 6–9 TWh).

6 Conclusions

The present study shows that the warming and increase in winter precipitation observed in Switzerland over the last century have influenced the water volumes available for hydropower production. The analyses were conducted on virtual intakes fed by water from mesoscale catchments. Comparing present conditions to previous periods, the strongest variations in discharge volumes available were found in glaciated catchments from the Swiss Alps. These areas currently deliver significantly more water than previously was the case. In lower-altitude regions of Switzerland, where discharge behaviour is dominated by precipitation, more water is available in winter and less water is available in summer than in the past. However, no significant changes in the annual available discharge volumes were found in these catchment areas. Overall, the observed climatic changes have given rise to more balanced discharge regimes, resulting in higher available water volumes for hydropower production and fewer production stops due to spillages or shortfalls. As a result, more electricity is produced today when compared with previous periods. Changes in Alpine areas were shown to be more important to Switzerland's total hydroelectric production than changes in lower-altitude areas. Alpine regions contribute a disproportionately high share of the total amount of water and have a remarkable long-range effect on large-scale river systems in lower-altitude regions, indirectly influencing the electricity production of distant power plants located along major rivers in Switzerland. Further, hydropower plants located in the Alps are able to use higher potential energies for power production.

The results of the present study mirror the annual observed electricity production, but caution is advised when directly comparing the study findings at seasonal time resolution with those of observed production: first, changes in rivers draining from the Swiss Alps were shown to have a greater impact on Switzerland's total electricity production than rivers in other regions. Second, the operation of storage hydropower plants results in reallocation of available water from one season to another, complicating the seasonal statistics. Even though winter runoff has increased significantly, summer runoff remains more important for the production of hydroelectric power when viewed in absolute terms. A key conclusion is that changes in hydrological conditions do not necessarily translate one to one into changes in hydropower production. Automatically equating changes in runoff with changes in hydroelectric production, as is done in many studies, is often misleading. To obtain more information about the impact of climatic changes on the water management of specific plants, more detailed analyses are needed (e.g. Hänggi et al. 2011a, b). In addition, climate-steered changes in the electricity market (demand side) must also be considered (e.g. Alfieri et al. 2006).

Acknowledgements This study is part of the Swiss Mountain Water Network initiated project "Climate change and hydropower generation in Switzerland". The project is funded by Swisselectric Research and the Swiss Federal Office of Energy (SFOE). Runoff data were provided by the Swiss Federal Office for the Environment (FOEN), Grande-Dixence S.A., and the cantons of Appenzell Ausserrhoden, Fribourg, St. Gallen, and Zurich.

References

Alexandersson H (1986) A homogeneity test applied to precipitation data. J Climatol 6(6):661–675

Alexandersson H (1995) Homogeneity testing, multiple breaks and trends. In: Steering Committee for International Meetings on Statistical Climatology, 6th International Meeting on Statistical Climatology. Galway, pp 439–442

Alfieri L, Perona P, Burlando P (2006) Optimal water allocation for an Alpine hydropower system under changing scenarios. Water Resour Manag 20(5):761–778. doi:10.1007/s11269-005-9006-y

Begert M, Schlegel T, Kirchhofer W (2005) Homogeneous temperature and precipitation series of Switzerland from 1864 to 2000. Int J Climatol 25(1):65–80. doi:10.1002/joc.1118

Belz JU et al (2007) Das Abflussregime des Rheins und seiner Nebenflüsse im 20. Jahrhundert: Analyse, Veränderungen, Trends. Lelystad

Beniston M (1997) Variations of snow depth and duration in the Swiss Alps over the last 50 years: Links to changes in large-scale climatic forcings. Climatic Change 36(3–4):281–300

BFKF (1995) Wahl, Dimensionierung und Abnahme einer Kleinturbine. Bundesamt für Konjunkturfragen BFKF, Bern

Birsan M-V, Molnar P, Burlando P, Pfaundler M (2005) Streamflow trends in Switzerland. J Hydrol 314(1–4):312–329. doi:10.1016/j.jhydrol.2005.06.008

Collins DN (2008) Climatic warming, glacier recession and runoff from Alpine basins after the Little Ice Age maximum. Ann Glaciol 48(1):119–124

Efron B, Tibshirani R (1993) An introduction to the bootstrap. Chapman & Hall, New York

Hänggi P, Weingartner R (2011) Inter-annual variability of runoff and climate within the Upper Rhine River basin, 1808-2007. Hydrolog Sci J 56(1):34–50. doi:10.1080/02626667.2010.536549

Hänggi P et al (2011a) Einfluss der Klimaänderung auf die Stromproduktion der Wasserkraftwerke im Prättigau 2021–2050. Fachbericht zur Synthese des Projektes Klimaänderung und Wasserkraftnutzung. Bern

Hänggi P et al (2011b). Einfluss der Klimaänderung auf die Stromproduktion des Wasserkraftwerks Löntsch 2021–2050. Fachbericht zur Synthese des Projektes Klimaänderung und Wasserkraftnutzung. Bern

Hubacher R, Schädler B (2010) Water balance of the main river basins during the 20th century. In: Landeshydrologie und -geologie (LHG) Hydrological Atlas of Switzerland. Plate 6.6. Bundesamt für Landestopographie, Bern

Huss M, Bauder A, Funk M, Hock R (2008a) Determination of the seasonal mass balance of four Alpine glaciers since 1865J Geophys Res - Earth Surface 113(F1). doi:10.1029/2007JF000803

Huss M, Farinotti D, Bauder A, Funk M (2008b) Modelling runoff from highly glacierized alpine drainage basins in a changing climate. Hydrol Process 22(19):3888–3902. doi:10.1002/hyp.7055

Khaliq MN, Ouarda TBMJ (2007) On the critical values of the standard normal homogeneity test (SNHT). Int J Climatol 27(5):681–687. doi:10.1002/joc.1438

Kundzewicz ZW, Robson AJ (2004) Change detection in hydrological records - a review of the methodology. Hydrolog Sci J 49(1):7–19

Laternser M, Schneebeli M (2003) Long-term snow climate trends of the Swiss Alps (1931-99). Int J Climatol 23(7):733–750. doi:10.1002/joc.912

Pellicciotti F, Bauder A, Parola M (2010) Effect of glaciers on streamflow trends in the Swiss Alps. Water Resour Res 46(10):W10522

Rapp J (2000) Konzeption, Problematik und Ergebnisse klimatologischer Trendanalysen für Europa und Deutschland. Bd. 212. Berichte des Deutschen Wetterdienstes. Deutscher Wetterdienst, Offenbach am Main

Scherrer SC, Appenzeller C, Laternser M (2004) Trends in Swiss Alpine snow days: The role of local- and large-scale climate variability. Geophys Res Lett 31(13). doi:10.1029/2004GL020255

Schmidli J, Frei C (2005) Trends of heavy precipitation and wet and dry spells in Switzerland during the 20th century“. Int J Climatol 25(6):753–771. doi:10.1002/joc.1179

Schmidli J, Schmutz C, Frei C, Wanner H, Schär C (2002) Mesoscale precipitation variability in the region of the European Alps during the 20th century. Int J Climatol 22(9):1049–1074

SFOE (2010) Swiss electricity statistics 2009/Schweizerische Elektrizitätsstatistik 2009. Swiss Federal Office of Energy SFOE, Bern

Viviroli D, Weingartner R (2004) The hydrological significance of mountains: from regional to global scale. Hydrol Earth Syst Sc 8(6):1016–1029

Weingartner R, Aschwanden H (1992) Discharge Regime - the Basis for the Estimation of Average Flows. In: Landeshydrologie und -geologie (LHG) Hydrological Atlas of Switzerland. Plate 5.2. Bundesamt für Landestopographie, Bern

Weingartner R, Pfister C (2007) To what extent was the hydrological winter drought 2005/06 exceptional? - a hydrological-historical review of streamflow in the river Rhine at Basel. Hydrologie und Wasserbewirtschaftung 51(1):22–26

Zappa M, Kan C (2007) Extreme heat and runoff extremes in the Swiss Alps. Nat Hazards Earth Syst Sci 7 (3):375–389

Zemp M, Haeberli W, Hoelzle M, Paul F (2006) Alpine glaciers to disappear within decades? Geophys Res Lett 33(13). doi:10.1029/2006GL026319