University of Zurich[UZH]

New analysis of low flow events and trends in the Alpine region over the last decades

GEO 511 Master's Thesis

Author
Michael Eichmann
16-719-015

Supervised by
Dr. Massimiliano Zappa (massimiliano.zappa@wsl.ch)
Luzi Bernhard (luzi.bernhard@wsl.ch)

Faculty representative
Prof. Dr. Jan Seibert

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Department of Geography, University of Zurich

University of Zurich[UZH]
Department of Geography

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Abstract

The Alps are a central element of the water supply for large parts of Central Europe. Many services such as agriculture, energy production, or even tourism are directly dependent on the Alpine runoff. At the same time, the Alps are an area that is particularly affected by climate change. This work aimed to investigate the typical low flow characteristics of the last decades of different regions in the Greater Alpine Region (GAR) and to derive trends regarding runoff volume and seasonality. We wanted to find out if all regions have changed equally or if there are differences between regions or other station characteristics. For this purpose, we assigned our catchments to different clusters based on their regime to make direct comparisons. We found that depending on the region, long-term runoff volumes are either decreasing (southern side of the Alps), constant (north of the Alps), or increasing (Alps). The changes are mostly due to runoff changes in spring and summer. We could prove these changes by analyzing the Pardé-coefficients over time. Furthermore, we examined individual years concerning low water events and made estimates for return periods of individual events. In the last step, we could show that Switzerland is a very good representation of the GAR and that the station behavior of a Swiss cluster can be well transferred to the corresponding one of the GAR.

Acknowledgements

Discharge data from Swiss stations were provided by the *Federal Office for the Environment* (FOEN). Data for the GAR are mostly from the *Alpine Drought Observatory* (ADO) database, supplemented by stations from *Ministère de l'Ecologie, du Développement Durable et de l'Energie* (France), *ARPA Lombardia* and *Ufficio Meteorologia e prevenzione valanghe* (both Italy). The author would also like to thank Manuela I. Brunner for the support and advice regarding the simulations, Luzi Bernhard for the explanations and help with the implementation of the program code on the server, Massimiliano Zappa for the discussions, advice, and tips throughout the work process, and Jan Seibert who served as the faculty member.

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Chapter 1

Introduction

Mountains have a decisive influence on the water supply in the surrounding regions. Therefore, they are also referred to as "water towers" (Viviroli et al. 2007) and provide the livelihood of many people. On the one hand, Alpine runoff is shaped by meteorological conditions such as precipitation and temperature; on the other hand, climatological and geographical characteristics also have a crucial influence (Lebiedzinski and Fürst 2018). Since the beginning of the 19th century, the temperature in the Alpine region has increased significantly, with an acceleration visible since the 1990s (IPCC 2014). The change in precipitation is more differentiated (e.g. Brugnara, Maugeri, et al. 2011). Both factors can have a considerable influence on runoff behavior. While changes in precipitation tend to affect the runoff volume, temperature changes control the temporal component of the runoff curve (Barnett et al. 2005). Changes in the flow regime can have impacts on ecological (e.g., biodiversity and water quality (Rolls et al. 2012)), economic (e.g., water supply, agriculture, transport, and energy production (van-Loon 2015)), and societal levels (e.g., tourism). This work aims to investigate changes in runoff behavior over the last decades. The special focus is on low water events and the spatial characteristics of individual extreme years. We performed the analysis in two parts; (I) stations within Switzerland and (II) stations of the Greater Alpine Region (GAR). We have made this subdivision because the data availability is not the same for both study regions. With this work, we try to transfer findings from the long-term runoff time series of Swiss stations to the GAR and to uncover differences between these two study regions. For this purpose, we collected daily discharge data from several hundred stations, including Austria, France, Germany, Italy, Slovenia, and Switzerland and categorized them depending on their regime type. Additionally to the observed records, we simulated 1500 years of discharge data for each station using the R-package 'PRSim'. The observed and simulated discharge data served as a basis for the calculation of the analyzed hydrological variables. In doing so, we try to answer the following research questions:

- (Q1) What are typical regime types in the Alpine space?
- (Q2) How has runoff changed over the past few decades, and do these changes differ across clusters?
- (Q3) What are regional differences of low flow events and extreme years?
- (Q4) Is a direct comparison between a cluster within Switzerland and the corresponding one within the GAR possible?

In the following chapters, we discuss the relevance of this topic by including literature and provide an overview of the used methods. We then focus on the results and discuss the given output. In the concluding chapter, the critical points of the thesis are summarized, and the research questions are answered. We also include a small outlook of what could be done for further research.

Chapter 2

Literature review

In terms of weather and climate records, the European Alps are one of the best-researched mountain regions in the world. Data have been collected for more than a century, and precipitation volumes are measured on various mountain peaks. Switzerland and Austria, in particular, operate some of the most permanent measuring stations, although the quality of the observations in this area is not always good. Another aspect that makes this region particularly interesting for climate studies is the diverse influence of different climate zones. The climate in the western part of the Alps is to a certain extent influenced by the oceanic climate of the French west coast. On the southern side of the Alps, we recognize influences of the Mediterranean while the climate north of the Alps shows continental components. In addition, the Alps themselves belong to the high mountain climate. (Beniston 2006)

The Alps are a fragile environment and particularly vulnerable to a changing climate. It can be seen, for example, from the temperature trends within the last 100 years. While temperatures have increased by about 1°C averaged over the entire northern hemisphere during this period (Gobiet et al. 2013), the change in individual regions is even more significant. In particular, landmasses are warming disproportionately fast because the heat storage capacity of the land is much less than that of water. If we consider only the landmasses, we find significant spatial differences, with the polar regions in particular, as well as the Alps, having warmed at an above-average rate. The Alpine region became warmer by about 2°C, and we can see an increasing acceleration of the temperature rise (Rebetez and Reinhard 2008). Between the years 1960-2010, this region warmed by about 1.5°C (Wang et al. 2014). These temperature increases also affect precipitation. Thus, warmer air has a larger water storage capacity (Clausius-Clapeyron equation), meaning more water can be transported to the Alps in terms of quantity, and precipitation is increased, especially during winter. At the same time, however, higher elevations lead to a precipitation change from snow to rain. Thus, precipitation is particularly relevant for Alpine runoff. General conclusions on the trends of precipitation totals and patterns are complicated because there are significant natural variabilities between subregions and the temporal component. For example, precipitation sums on the southern side of the Alps have tended to decline in recent decades. This decrease was particularly marked in the winter and spring months (Brugnara and Maugeri 2019). A similar pattern emerges for the Tyrol region, where the average annual precipitation sum decreases by about 1 to 1.5 % per decade (Brugnara, Maugeri, et al. 2011). In contrast, there are measuring stations in the northwest of the Alps where precipitation sum has increased, primarily due to the winter with more precipitation (Auer et al. 2005). In the area of Switzerland, some precipitation stations record data back to 1864. Considering only stations on the northern side of the Alps (below 1000 m a.s.l.), there is a tendency to increased precipitation throughout the year. However, this trend is mainly due to the higher winter precipitation (a slight decrease in autumn). For southern Switzerland, on the other hand, no clear trend can be identified. The increasing winter precipitation is entirely compensated by drier months in autumn (for more details and observed trends visit: `https://www.meteoswiss.admin.ch/home/climate/climate-change-in-switzerland/temperature-and-precipitation-trends.html` [last access: 06/25/21]).

Averaged over the GAR, a shift of the precipitation maximum from summer to winter can be observed (BMU 2008). Furthermore, higher elevations change the form of precipitation in winter from snow to rain. Changes in the Alpine climate are closely coupled with extreme events. The European Environment Agency (EEA) assumes that such extreme events will occur more frequently and more often as a result of climate change (EEA 2016).

Glaciers play an equally important component in determining (high) Alpine runoff. They store large amounts of water, which is supplied to streams by the melting process in spring. Rising temperatures are affecting the glaciers, and since the beginning of the 20th century, about half of the ice mass has been lost (Huss 2012; Zemp et al. 2008). If this climate trend continues, an additional 80% (climate scenario RCP 4.5) could disappear by 2100 (Radić et al. 2014).

However, Alpine runoff is controlled and modified by climatic factors and direct human influences. Examples of such anthropogenic influence are dams or hydropower plants, which are used to generate electricity. According to a study from 2005, about 3/4 of all major rivers in the Alpine region had been altered by at least one structural measure by that time (Nielsson et al. 2005). Dams have a particular effect on the highly variable discharge pattern within a year so that the amplitude variation becomes smaller.

The Alps and the immediate region are of enormous importance for a large part of

Central Europe. About 14 million people live or work in this vulnerable region (Alpine Convention 2011). Moreover, the Alps, especially the large water availability, are the basis for various ecological services. These include, as already mentioned, the production of energy, but also agriculture, forestry, drinking water supply, and tourism. A change in runoff dynamics and volumes, therefore, has a direct impact on all these sectors and is therefore of utmost importance (Egarter-Vigl et al. 2016). Furthermore, dams not only change the runoff characteristics but also affect the water quality (for example, by changing the sedimentation process) (Gabbud and Lane 2016) and thus have an impact on the fish population (Rolls et al. 2012). On the other hand, past discharge developments, as well as future trends, are of great importance, especially for hydropower plant operators, and uncertainties should be minimized as much as possible (van-Loon 2015). However, the EEA also sees the risk of increasing tensions between the different water users in a changing discharge behavior (EEA 2016).

Chapter 3

Methodology

In this chapter, we will describe the methods we used for our analyses. The chapter is divided into two sections, the first of which deals with the clustering procedure and provides the basis for the clustering. Based on these different clusters, we made some hydrological analyses and evaluations, whose methodology will be explained in more detail in the second part of this chapter.

3.1 Clustering

3.1.1 Regime curves

We have several hundred hydrological discharge stations in our study regions. Since the runoff behavior can vary considerably depending on the region and therefore significantly influences the analyses, we have divided our data set into individual clusters. There are several classification methods. Two of the most common are either classification by macro-region or by flow regime, which is widely used in hydrology (see, e.g., Lebiedzinski and Fürst 2018). Regime curves have the advantage of not having mixed runoff characteristics within a cluster, but this process is somewhat more laborious than categorizing by macro-region. We decided to categorize by regime curves since one of our goal was to describe the typical regime types in the Alpine region.
To determine the regime curves, we used runoff data of 30 years (according to the most available stations we used the period 1988-2017 for Switzerland and 1982-2011 for the GAR, see appendix A.1). We calculated both the average runoff volume of each month and that of the entire year. Dividing the annual runoff by 12 gives the average expected volume of a month if the runoff was constant throughout the year. The actual monthly value (MQ_i) is set to the expected value (MQ), with values above 1

describing months with above-average runoff and values below 1 describing those with below-average runoff (see Eq. 3.1). This value is called the Pardé coefficient (Pardé and Kolupaila 1933) and has the advantage of making catchments directly comparable to other catchments, regardless of their size or runoff volume. The monthly Pardé coefficients for catchments in our study region typically vary between 0.5-3 over the year. However, theoretically, all values between 0 (month with no runoff) and 12 (total annual runoff in that month) are possible. Thus, if we take all the monthly Pardé coefficients of one catchment, we obtain its regime curve.

$$PK_i = MQ_i/MQ \tag{3.1}$$

Before we could perform the actual cluster classification, we had to define the number of different clusters. For this process, using all the regime curves, we applied the k-Means clustering algorithm (MacQueen 1967) and gradually increased the number of clusters from 1 to 10. The regime curves were then divided according to the number of clusters, and subsequently, the squared deviation of all regime curves within a cluster group was determined. As the number of clusters increases, this difference decreases because there are fewer clusters with mixed regimes, but an increase in the number of clusters also results in comparability becoming more complex. Thus, an ideal number of clusters have low internal differences of all regime curves and grant visual differences between the individual clusters. Therefore, we determined the ideal number of clusters for our data set to be six. Having determined the ideal number, we now used the k-Means clustering algorithm to categorize the regime curves. We used the k-Means clustering algorithm version of Hartigan and Wong 1979 which can be summarized the following: The algorithm randomly selects six (ideal number) of all regime curves, which are defined as cluster centers. All remaining regime curves are assigned to a center so that the smallest Euclidean distance results. After all regime curves have been assigned, the new center of each cluster is calculated. Based on the new centers, all remaining regime curves are again assigned to the most similar cluster. This process of recalculation-assignment is repeated until the center does not change between two calculation steps. Once this process has finished, we reached the best regime curve classification under the condition of six clusters.

3.1.2 Delayed flow separation

Runoff from a stream is made up of several components, often referred to as quick- and baseflow, with quickflow representing direct runoff (e.g., precipitation input) and baseflow representing runoff from delayed sources such as groundwater or snow (Stoelzle et al. 2020). However, there are various definitions of baseflow, and therefore different baseflow separation techniques exist (e.g., Eckhardt 2008). The study by Stoelzle et al. (2020) goes one step further and tries to separate the streamflow in more than just quick- and baseflow. Their work is based on the widely used UKIH baseflow separation method (a detailed description of this technique can be found in Piggott et al. 2005). This method aims to identify streamflow minima in a consecutive period of N (block size) non-overlapping days. As a result of linear interpolation of these minima, a continuous baseflow hydrograph is obtained. This hydrograph is directly dependent on the chosen block size length N. Stoelzle et al. extended the UKIH approach and additionally developed a delayed-flow index, which captures the dynamics of multiple delayed contributions. They tested the method by using runoff data from Switzerland and Germany and concluded that a N of 60 days is sufficient to capture all minimum discharges of the catchments without losing additional information of the streamflow variability. Using characteristic delay curves (CDC), they then determined three breakpoints so that a linear interpolation between these points would show as little difference as possible from the calculated values (minimizing the residual sums of the resulting three linear regression lines (Muggeo 2008)). As a result, all catchments have slightly different block sizes for the individual breakpoints. Even if the differences are only minor, no generally valid statement can be made about the exact block sizes of individual delay classes. However, it can be said that outflows with a residence time of more than 60 days are counted as part of the baseflow (baseline). Short-delay contribution usually includes outflows with a residence time between 0-5 days, intermediate-delay between 5-15 (but also up to 30 possible), and long-delay between 15 (30) and 60 days. In general, catchments with high streamflow dynamics have steeper CDCs, while catchments with large proportions of baseflow showing less distinctive CDCs (Stoelzle et al. 2020).

3.2 Low flow analysis

3.2.1 Stochastic simulations

Stochastic generated simulations of runoff data are widely used in hydrology. Applications can be found primarily in water management, extreme hydrological events such as floods and droughts, or for the generation of realistic but previously unobserved runoff series (Borgomeo et al. 2015). Such simulations aim to provide a robust data basis. In doing so, the simulations should conserve the typical characteristics of a hydrograph (e.g., discharge means, variance, and seasonal patterns) as realistically as possible (Salas and Lee 2010). For our simulations, we used the R package 'PRSim',

which simulates annual hydrographs in the Alpine region well (Brunner, Farinotti, et al. 2019a).
Its stochastic simulation process is based on seven steps (adapted from Brunner, Bárdossy, et al. 2019b):

1. Fitting of theoretical kappa distribution: This distribution allows to obtain extreme values beyond the empirical distribution and is used in the last step for the back transformation. Brunner et al. were able to show that the kappa distribution provides a good fit for Alpine catchments.
2. Normalization and deseasonalization of the marginal distribution: The outflows of each calendar day are normalized separately to exclude the seasonality of the data.
3. Fourier transformation: The deseasonalized and normalized discharge data are converted from the time domain to a frequency domain using the Fourier transformation.
4. Random phase generation: Sampling from uniform phase distribution while maintaining the observed spectrum.
5. Inverse Fourier transformation: Transform the data from frequency back to the time domain.
6. Back transformation: Using the kappa distribution (step 1), the data are back-transformed from the normal to the kappa distribution.
7. Simulation: Repetition of steps 4-7 to generate the desired number of simulations (each with the same length as the observed (input) time series)

3.2.2 Return period

A suitable measure to quantify and estimate low water events is the so-called "return period". Using long time series, discharge events of specific periods (usually years or months) can be evaluated and compared with the long-term norm. The further the measured value is from the norm, the rarer the event (i.e., the higher its return period). There are different approaches how to calculate such return periods. Either they can be determined by a theoretical distribution function (e.g., Weibull distribution) or by empirical calculation using plotting position. The use of a theoretical distribution function requires a large sample because otherwise, extrapolations are made into areas where only a few data are available, which makes the results very fragile (a good example is a study by Van-der-Wiel et al. 2019). The stochastic simulations increase the sample size, but then the extrapolation is done twice (once within the simulation and once with the theoretical distribution function). Therefore, we have chosen the empirical approach. The advantage is that we can increase the sample size by stochastic simulations without a second extrapolation within the calculation of the return period. For all relevant stations, we, therefore, performed 50 simulations, all covering 30 years. They gave us 1500 simulated years each, which could be used as a basis for the empirical calculation of the return periods. The calculation of a return period of a minimum 7-day discharge event is used as an example to illustrate the Weibull position plotting procedure (Makkonen 2005):

1. We determined the minimum 7-day discharge for each of these 1500 simulated years and plotted them in increasing order (minimum 7-day discharge vs. index of the simulated year)

2. Using Weibull position plotting, we determined the exceedance probability (P) for all minimum 7-day values so that the probability of the lowest value is 1/1501, and the probability of the highest is 1500/1501

3. The return period is simply the inverse of P, i.e., 1/P, and can be calculated for the entire run, yielding a falling curve (minimum 7-day discharge vs. return period)

4. The actual measured minimum 7-day discharge values of all 30 years can be taken and fitted to this curve, where the respective return period can be read off directly

For full-year calculations, we considered the complete time series of the 1500 simulated years. In contrast, if we quantified the return period of an event in a particular month, we used only the simulated data of that month. This procedure prevents the data from being influenced by the seasonally varying discharges.
A shortcoming of this relatively simple method is that return periods can be only as high as their sample size (in this example, 1500 years). Thus, all measured values that fall below the empirically calculated lowest value are automatically assigned the highest return period (1500 years).

3.2.3 Pardé change calculations

To describe the discharge change of a catchment area over time, we performed a temporal evaluation of the Pardé coefficient. For stations within Switzerland, we could

rely on a data series of 90 years, within the GAR at least 50 years. Regime curves are an excellent method to describe the runoff behavior of a catchment, and they are also suitable to determine changes between two points in time (e.g., Bormann 2010).
For our evaluation, we proceeded similarly to the study of Lebiedzinski and Fürst 2018, which also investigated temporal runoff changes in the Alpine region (Austria). First, we calculated each station's average regime of the first 20 years of a data series. Then, step by step, we moved this 20-year data window forward by one year and repeated the regime calculation after each step. For the 90-year data series of Swiss stations, this resulted in a total of 71 time steps (1928-1947, 1929-1948, ..., 1998-2017) for the remaining stations in the GAR there were 31 (1961-1980, 1962-1981, ..., 1991-2010). Like Lebiedzinski and Fürst, for each 20-year data window, we excluded the one year which had the highest monthly discharge (and therefore also the highest Pardé coefficient). We did this for the simple reason that even one year with an extreme flood event would have a considerable impact on the regime curve, and thus natural variability could somewhat mask the long-term trends. Finally, to quantify the changes in a cluster region, we used the average regime curves of all stations belonging to the cluster.

Chapter 4

Data and Cluster

4.1 Switzerland

The analysis of the stations within Switzerland comprises a total of 152 stations. The stations are distributed rather homogeneously and cover all specific regions like the Jura region, the Plateau or the Alps, and the Ticino. The measuring stations represent (sub-)catchments of different sizes and at different altitudes. The smallest represented catchment measures only 0.56 km^2, the largest 35'878 km^2. The average catchment elevations range between 467 and 2937 m a.s.l. (station elevations between 202 and 1860 m a.s.l.). The data were provided from the official FOEN station network and supplemented by individual cantonal discharge measurements. Depending on the evaluation, we used consistent time series between 30 and 90 years. The station network was divided into subgroups using the k-Means clustering algorithm so that stations with similar regime characteristics were grouped (Figure 4.1). In total, we thus formed six cluster regions whose typical properties are briefly summarized below and classified to a regime type according to Weingartner and Aschwanden 1992:

1. Jura (pink, number of stations (n) = 34): This regime has typical Pardé variations between 0.4 and 1.6. The highest Pardé coefficients occur during winter, especially in March. From spring to late summer, the values constantly decrease, typically reaching the lowest values in August. During the fall, relative discharges usually increase again. This annual pattern corresponds to the 'pluvial jurassien' regime.

2. Large catchment (brown, n = 26): The 'Large catchment' comprises particular stations on large rivers, such as the Rhine or the Rhone. The average annual course of this regime has its highest discharge during early summer (June), with

values of about 1.7. The lowest values are just above 0.5 and are usually reached in the winter half-year (January). Thus, most of the runoff occurs between April and September. According to the table of Weingartner and Aschwanden, this course corresponds to the 'nivo-pluvial préalpin' regime.

3. Plateau (cyan, n = 39): This one has the highest number of stations of all the clusters. The annual discharge fluctuations are particularly low. One can see a slightly higher discharge during spring and early summer, but the Pardé coefficients are not very high, with a maximum of 1.3. The lowest discharges occur during winter (especially at the beginning of winter) but are rarely below 0.8. A typical discharge pattern of catchments within the category 'pluvial supérieur'.

4. Alps (orange, n = 35): Stations with catchments at higher elevations usually show more pronounced intra-annual discharge variability. One can see the low discharges during winter. From April onwards, runoff increases significantly and reaches its maximum level between May and July, depending on the station. The decrease in runoff in the fall is less rapid than the increase in the spring and continues to level off. These stations show most of the characteristics of the 'b-glacio-nival'.

5. High-Alps (red, n = 10): Of all the clusters, the one with the highest variability within a year (between just above 0 to about 3). The low values at the beginning of the year indicate shallow discharges, which only rise slowly from April and reach their peak in late summer. Rapid decrease in subsequent months so that

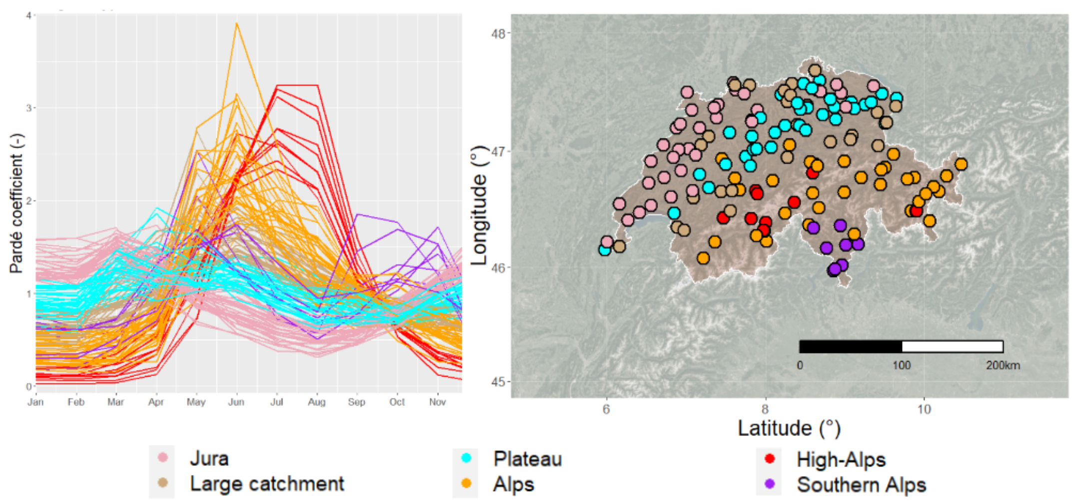


FIGURE 4.1: (Left) Averaged (1988-2017) yearly regime curves for the 152 stations. The colors represent the different clusters generated using the k-Means clustering algorithm. (Right) Spatial representation of the stations colored by cluster.

virtually all annual runoff occurs between April and November. Stations in this cluster are either of an 'a-glaciaire' or 'b-glaciaire' regime.

6. Southern Alps (purple, n = 8): The only cluster with a typical two-hills shape. Below average discharges in the winter months followed by the first discharge peak in May, which is somewhat more pronounced than the second peak in October. Between the two peaks, a significant decrease in discharge (Pardé below 1). The classification of such runoff regimes corresponds either to the 'pluvio-nival méridional' regime, although tendencies towards the 'nivo-pluvial méridional' with a somewhat more pronounced first peak can also be seen.

Figure 4.2 gives a detailed overview of the distribution of catchment altitudes divided into six different clusters. The first cluster group ('Jura') comprises mainly stations with an average catchment elevation between 700-900 m a.s.l., larger outliers are seen only very few. A somewhat larger variation in catchment elevation occurs for stations of the second cluster ('Large catchment'). These are located on average at an elevation of about 1400 m a.s.l., with individual stations also representing catchments below 1000 and above 2000 m a.s.l., respectively. The 'Plateau' cluster has a median elevation of about 1000 m a.s.l., and generally small differences. All stations within the cluster 'Alps' represent catchments above 1500 m a.s.l., most of them even above 2000 m a.s.l. A similar picture emerges for the cluster of 'High-Alps'. All those catchments have

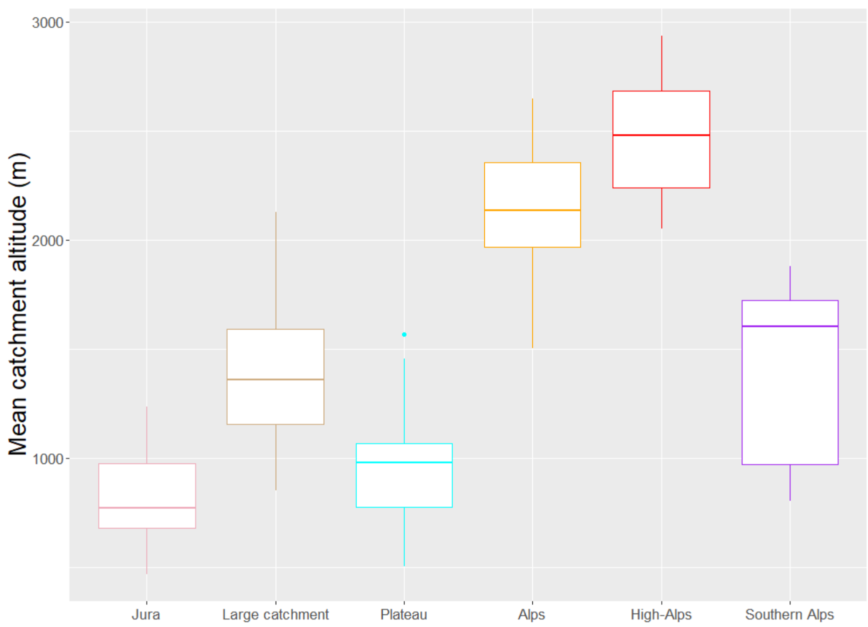


FIGURE 4.2: Mean catchment altitude by cluster. The box represents the center 50 % of the stations, with one half below and the other above the horizontal line (median). Single data points indicate outliers with more than two standard deviations.

average elevations between 2000-3000 m a.s.l. with about half of all above 2500 m a.s.l. The 'Southern Alps' have the largest within-variability of all clusters, with mean elevations between the two Alpine clusters and the three clusters north of the Alps (1000-1800 m a.s.l.).

At first sight, the catchment sizes do not seem to be as different as the altitudes. Except for 'Large catchment', most catchments are significantly smaller than 400 km^2. In particular, the 'High-Alps' have very small catchments, and only minor differences in sizes can be discerned. Some larger catchments exist for both the 'Alps' and 'Plateau'. The median of the 'Large catchment' group is at least five times higher compared to all other clusters (4.3).

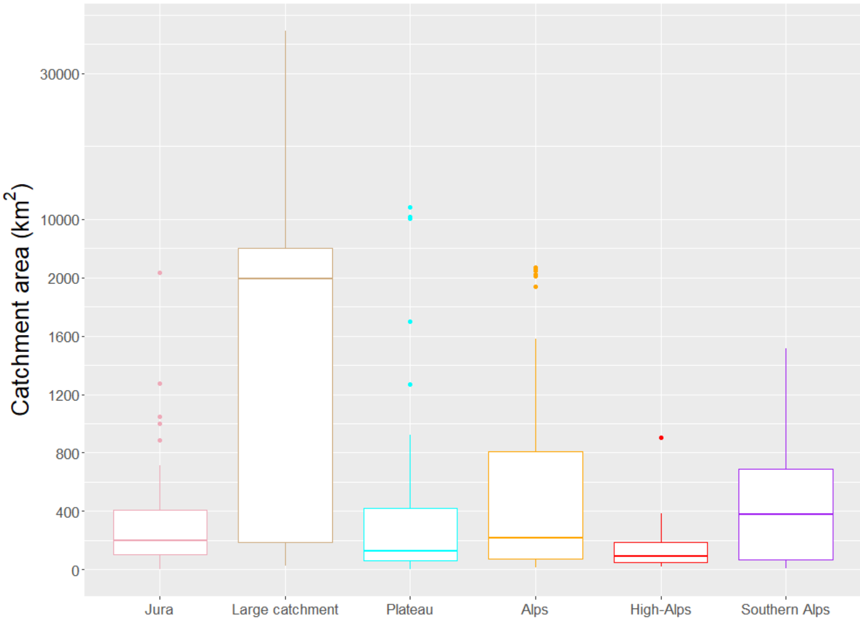


FIGURE 4.3: Same as Figure 4.2 but for catchment size. Note the irregular y-axis to better represent the large variation.

4.2 Greater Alpine Region

The data set for the Greater Alpine Region (GAR) is significantly larger than that of Switzerland and includes 527 stations. The 30-year time window, from which we have most of the runoff data, covers at least 1982-2011. It is slightly shifted compared to the Swiss data but is since, depending on the country, the validation process and publication of the current data can take somewhat longer. While the stations in Switzerland were spatially homogeneously distributed, this looks a little more differentiated for the stations within the GAR. Especially in the Italian region, the data density is relatively low or partly missing, to a certain extent due to the lack of a national data network.

A second reason can be attributed to data acquisition. Our data (apart from Swiss stations) come from the database of the 'Alpine Drought Observatory' project (ADO). The ADO project aims to develop an online drought monitoring platform that, among other things, will improve the forecasting of drought in the GAR. For this project, mainly stations with a catchment size of >1000 km^2 are used, which means that stations from smaller catchments are not equally well covered.
The stations represent catchment sizes between 0.56 km^2 and 95'970 km^2, with only 14 stations exceeding an area of 20'000 km^2. The average station elevation is 534 m a.s.l., ranging between 1-1995 m a.s.l. It should be noted that, unlike the evaluation of the Swiss data, only the station elevation rather than the average catchment elevation were available (generally lower).
One aim of this work is to determine and analyze low water discharges in the GAR. However, we also want to determine whether the data and time courses of low water events in Switzerland can be transferred to the GAR and if stations with the same regime curves differentiate between the two study regions. To ensure the comparability of these two data sets, we decided to use the same categories for the clustering of the GAR as we did for Switzerland. Therefore, we calculated the average annual regime curve for all six (Swiss) clusters and assigned each station of the GAR to the cluster where the difference between its regime curve and the regime curve of the cluster average was the smallest. The spatial distribution of the resulting clusters and the regime curves can be found in Figure 4.4 (since the categorization was done by similar regime curves, the above-described characteristics are also valid for the corresponding clusters of the GAR and the following list therefore focus more on the spatial distribution of the clusters):

- Jura (pink, number of stations (n) = 140): The stations are distributed in particular over the northern part of the GAR. However, individual stations with 'pluvial jurassien' runoff characteristics are also found outside the Jura region, namely for some stations in Slovenia and western France in the base of the Alpine ridge.

- Large catchment (brown, n = 91): A very limited spatial range of measuring stations on the northern side of the Alps. This 'band' extends from the Lake Geneva region to Niederösterreich. South of the Alps, this regime type occurs just very rarely.

- Plateau (cyan, n = 196): This very balanced flow regime of the 'pluvial supérieur' not only occurs most often but also in almost all regions of the GAR. However, the main concentration is in the western French region as well as in the Swiss Plateau, with some single stations in southern Germany.

- Alps (orange, n = 64): Most stations of this cluster are located in Switzerland and Austria. There are only very few Alpine stations within the French and Italian parts of the Alps.
- High-Alps (red, n = 23): Similar pattern as 'Alps', but all stations with a high Alpine runoff character are located either in Switzerland, Austria, or Italy. A small cluster of stations each in the Bernese Oberland and the Grossglockner region.
- Southern Alps (purple, n = 13): Of all clusters, the one with the fewest stations. A runoff regime with the typical two-peaks runoff occurs only on the southern side of the Alps in the region of Ticino and on the border between Italy and Slovenia.

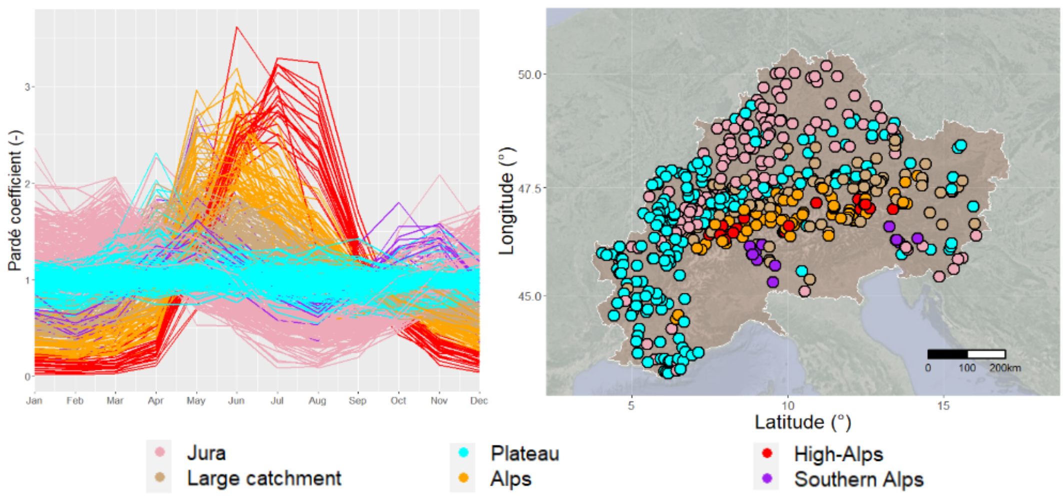


FIGURE 4.4: Same as Figure 4.1 but for the 572 stations in the GAR. The color scheme follows the same structure as in Switzerland.

The map shows that the cluster sizes are much more variable than within Switzerland. The two largest clusters ('Jura' (140) and 'Plateau' (196)) cover around 60 % of all stations. The fewest stations are found south of the Alps (13) and in the 'High-Alps' (23).

Figure 4.5 is not directly comparable with the corresponding representation of the Swiss stations, since here, as already mentioned, the elevation of the station and not the mean catchment area elevation is shown. The stations of the 'Southern Alps' are on average the lowest with approximately 300 m a.s.l. The 'Jura' and 'Plateau' are comparable, with the latter having a slightly more extensive range. On the other hand, 'Large catchment' are on average at an elevation of just over 500 m a.s.l. with some stations located at 1000 m a.s.l. The 'Alps' and 'High-Alps' are at significantly higher elevations and just under 900 and 1300 m a.s.l. respectively.

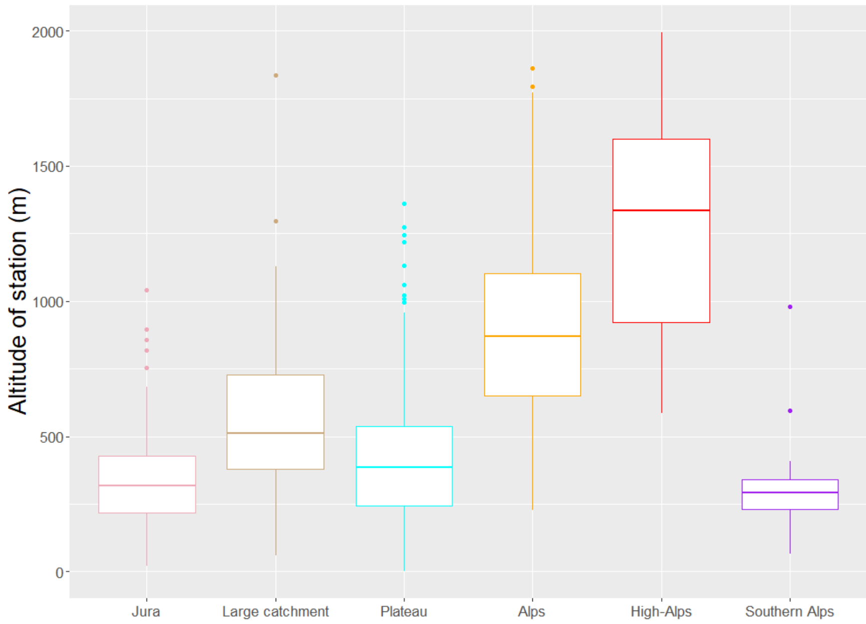


FIGURE 4.5: Same as Figure 4.3 but instead of mean catchment elevation (not available), the elevation of the station itself is represented.

A detailed view of the catchment areas is shown in Figure 4.6. The stations assigned to the 'Jura' cluster comprise mostly smaller catchments (about 75 % have an area $< 1000\ km^2$). The median is just under 300 km^2, with a few outliers over 10'000 km^2. The distribution for the category 'Alps' looks quite similar. Here, too, most are well below 1000 km^2. The generally smallest catchments belong to the 'High-Alps'

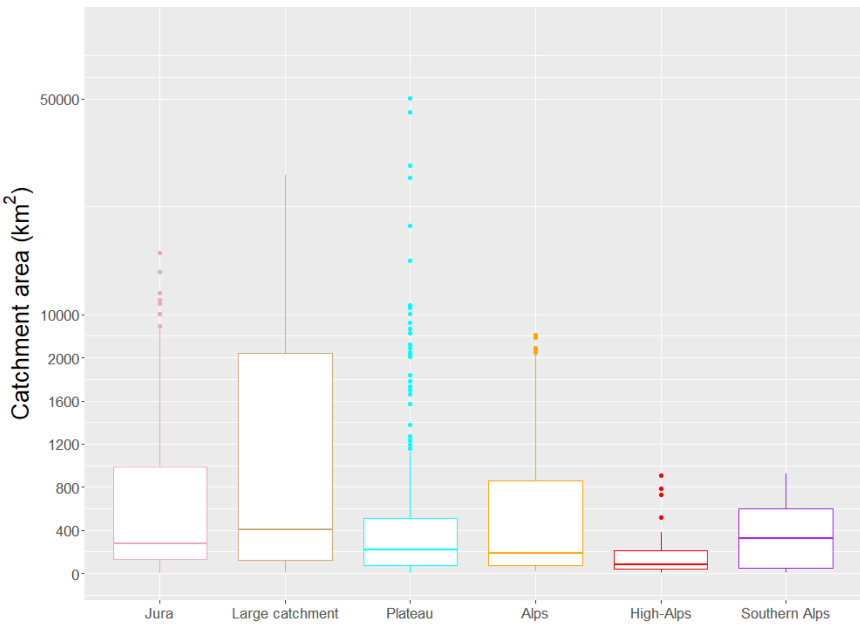


FIGURE 4.6: Same as Figure 4.3

cluster, with none larger than 1000 km^2. The largest catchments belong to the 'Large catchment' cluster. Here, some stations represent catchments well over 10'000 km^2 (the two largest outliers 76'653 and 95'970 km^2 are not shown). Finally, 'Plateau' and 'Southern Alps' also have hardly any stations with catchment areas < 600 km^2.

Chapter 5

Results

5.1 Switzerland

In the first section, we present the results of the analyses for the stations of Switzerland. There are two parts with different lengths of time series used. In the first part, we used daily discharge time series of 90 years. With long time series, it is possible to carry out some long-term analysis such as the 'Annual discharge trend' or observe changes in the regime curves ('Pardé changes'). In the second part, we used a time series of 30 years to analyze extreme year observations, minimum 7-day discharge trends, and duration/magnitude of low flow events. Forty-eight stations have a daily discharge record of at least 90 years and 152 stations with a 30-year discharge series.

5.1.1 Discharge contribution

We separated the discharge using the same method as Stoelzle et al. 2020 and summarized the relative contributions of the four delay classes per cluster (Figure 5.1). Across all clusters, the relative contribution of baseflow to total runoff is most considerable at stations in the 'Large catchment' group (about 40 %). Within 'Jura', 'Plateau', 'Alps', and 'Southern Alps', the relative contributions are about the same and range between 30-35 % each. Significantly smaller contributions of baseflow to total discharge are observed at stations in the 'High-Alps' (about 10 %). The three delay classes quantify the runoff with a residence time between 0 and 60 days, where a residence time between 0-5 days (approximately) is considered a short-delay contribution. This contribution is particularly high for stations in the 'Southern Alps', 'Jura', and 'Plateau' regions, with about 35 % of the total runoff volume. Somewhat lower relative contributions between 20-25% were calculated for the remaining three clusters. Large differences also exist for the runoff contributions with an intermediate residence time. While about half of the total runoff volume of the 'High-Alps' was classified as intermediate delay, the contribution in the cluster 'Large catchment' is only about 15 %. The other clusters have contributions between 20-25 %. In general, runoff contribution with a long residence time is rather low, although some differences between the individual regions can be found. The contribution is largest for the Alpine stations ('Alps' and 'High-Alps'), accounting for about one-fifth of the total runoff. Somewhat smaller contributions (about 10 %) are made by water with a long residence time in the 'Jura' and 'Plateau' regions.

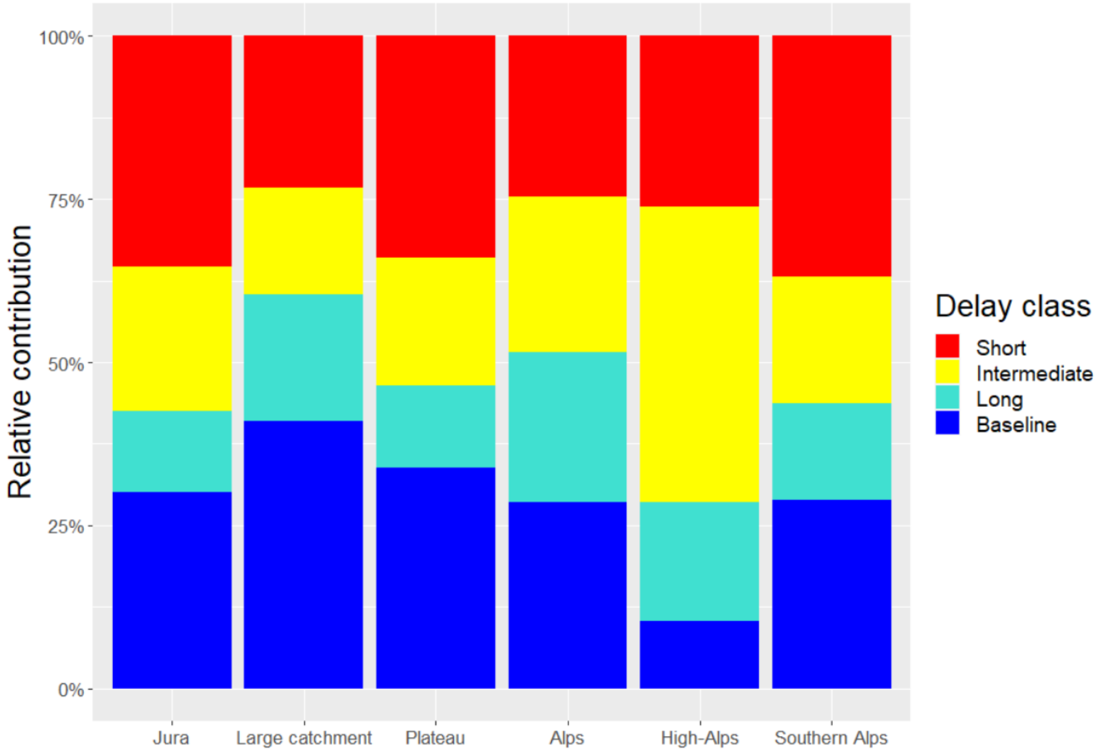


FIGURE 5.1: Relative contribution of the four delay classes by cluster. The values are calculated using discharge data of the period 1988-2017. For each cluster the mean of all corresponding stations was considered.

5.1.2 Long-term discharge trend

The discharge behavior of Swiss rivers has changed over the past decades. On the one hand, a temporal shift of the seasonal discharge (especially in high-elevation regions) can be observed, and on the other hand, there are trends regarding the annual discharge (e.g., Birsan et al. 2005). Using our 90-year time series, we have examined these trends in more detail for all six clusters within Switzerland. Our data set includes 48 stations but with only two stations each available for 'High-Alps' and 'Southern Alps'. To visualize stations of the same cluster in one graph, we normalized the annual discharge of all stations (the maximum value per station was set to 1, all other values were put into the ratio to that value). Figure 5.2 shows the annual curves of all stations. We have expressed the trends as a percentage change per decade (top right). For the stations within the clusters 'Jura' and 'Plateau' we found a decrease, for the 'High-Alps', an increasing trend (1928-2017), but all these changes are not significant ($p > 0.05$). Two possible explanations may be the small number of stations ('High-Alps') as well as small changes ('Plateau'). For stations within 'Large catchment' and 'Southern Alps', we found slightly significant changes ($0.01 < p < 0.05$), with a decrease in discharge over time measured for both clusters (-0.4 %/dec and -1.56 %/dec, respectively). We found the most significant changes with $p < 0.001$ for the 'Alps' region, where the runoff has decreased by about 1.5 % per decade.

The evaluation of trends by season shows a more differentiated pattern. For the

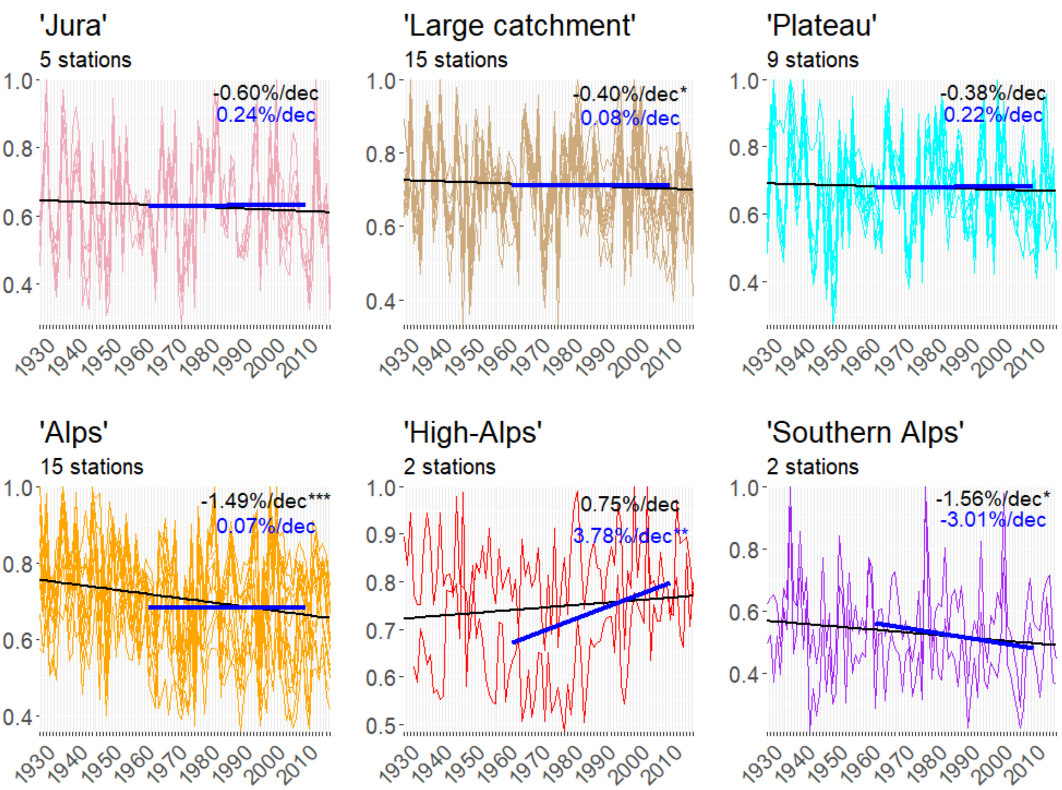


FIGURE 5.2: Trend of the annual discharge volume by cluster (1928-2017). The y-axis represents normalized annual runoff totals, with 1 representing the year with the highest runoff. The numbers in the upper right show the percentage change in discharge volume per decade (black numbers correspond to the black trendlines, blue numbers to the blue trends). The asterisks behind the numbers indicate the statistical significance of these changes, with p-values below 0.05 (*), below 0.01 (**), and below 0.001 (***) shown differently. The blue trendlines (1961-2011) are shown to compare with the GAR stations directly.

sake of clarity, the individual curves of the 48 stations are not shown in Figure 5.3, but only the mean trendline of each cluster. For the winter months, we have positive outflow trends in all clusters. The increases are most pronounced in the 'Alps' with more than + 6 %/dec, but also 'Jura' and 'Large catchment' show significant increases (+ 2.33 %/dec and + 3.84 %/dec respectively). The 'Plateau' and 'High-Alps' trends are also significant but not as pronounced as those already mentioned. Only 'Southern Alps' does not show a statistically significant trend ($p > 0.05$). Changing rates for the spring are generally lower, and only half of the clusters have significant increases ($p < 0.001$). The trends of the others are mixed. While 'Jura' and 'Southern Alps' tend to show increasing runoff, the stations of the 'Plateau' show rather negative trends. The season with the biggest relative changes is the summer. All but 'High-Alps' show a tremendous decrease in discharge (between - 1.23 %/dec and - 4.07 %/dec). The p-value is for four out of these five regions highly significant. The only exception is 'High-Alps'. Those stations observed an even increasing discharge during this time period ($p > 0.05$). The discharge behavior in fall is negative but not as significant as during the summer months. The highest changes in percent are observed in 'Jura'; the highest significance can be found in 'Alps'.

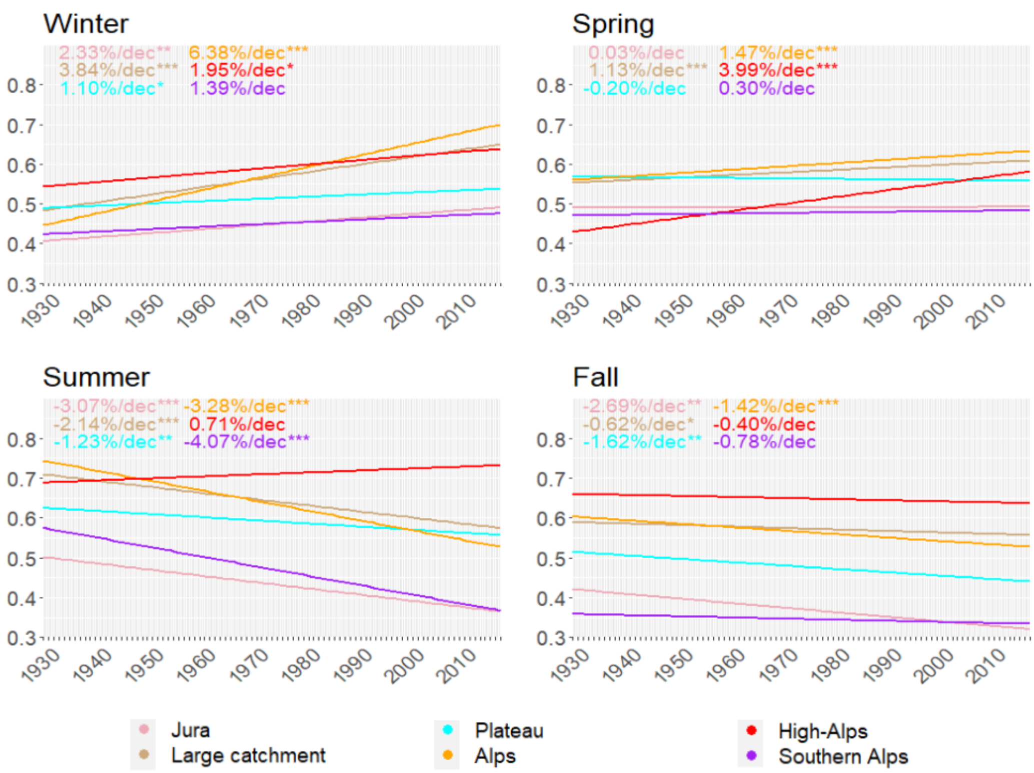


FIGURE 5.3: Same as Figure 5.2 but on seasonal level and for the sake of readability only the mean trendlines per cluster are shown.

5.1.3 Pardé change

Using the same 90-year data series, we evaluated the change in regime curves over the decades. To do so, we calculated the regime curves three times, each with a different time window (20 years for each case). Figure 5.4 shows the three curves for the individual clusters.

Time periods include 1928-1947 (green), 1963-1982 (black) and 1998-2017 (blue). In the region 'Jura' we can see changes throughout the year. Especially the summer months show less discharge in recent years, the Pardé coefficients for these months decreased by about 0.2. On the other hand, the regime curves during the first quarter of the year tend to be higher, and also December shows more runoff contributions in recent years. The amplitude constantly increased over time, with variations between 0.5-1.55 for the third period compared to 0.55-1.45 within the first period. For 'Large catchment' the changes look similar. Again, the Pardé coefficients for the summer months have decreased significantly over time (from an initial 1.75 to about 1.55). This deficit is "compensated" especially in winter. However, the amplitude variation is decreasing for these stations, and the current discharge is more balanced over the

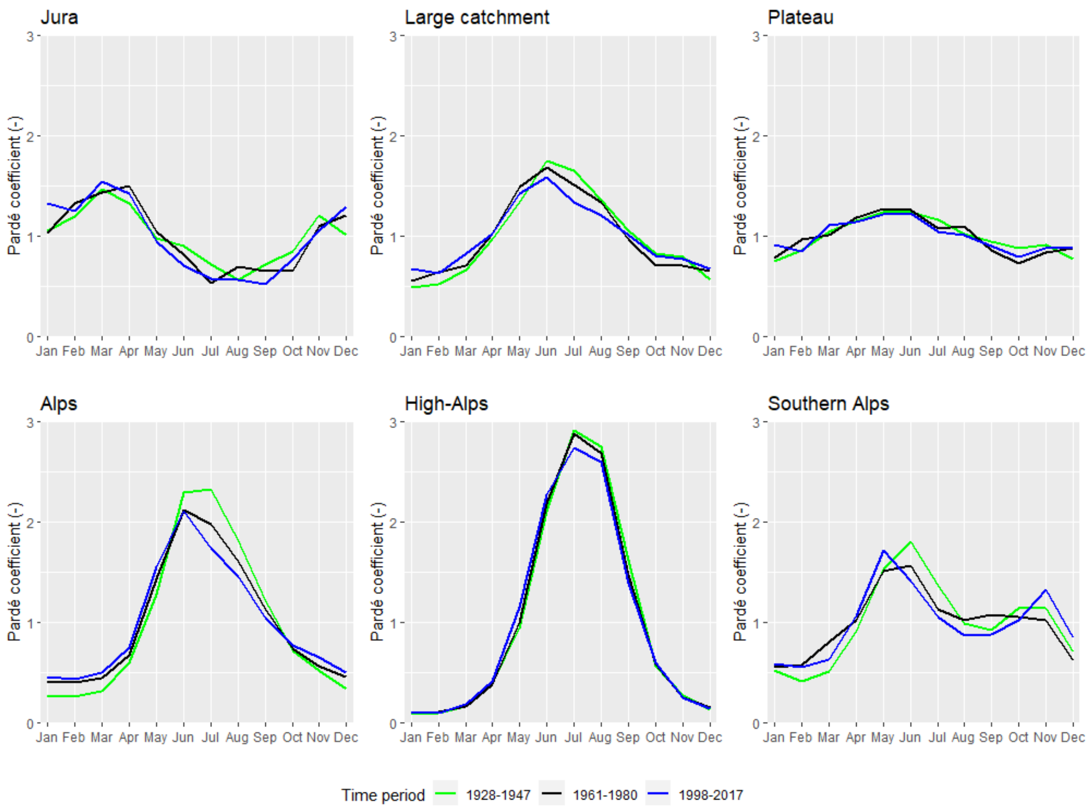
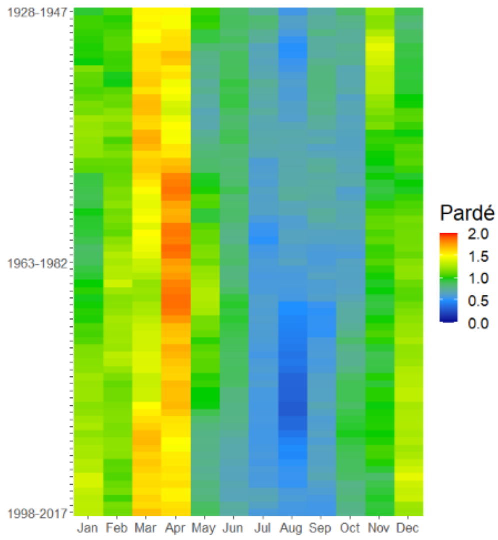


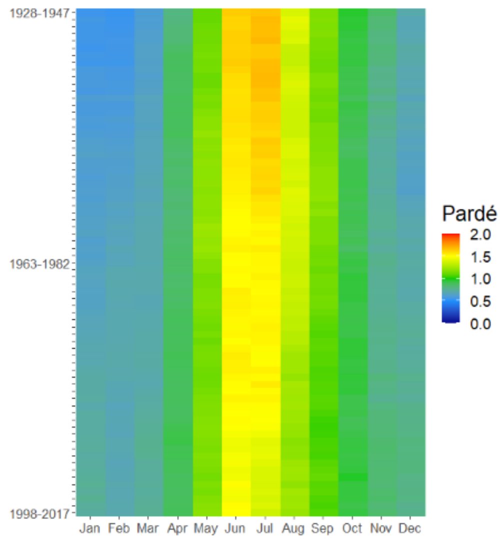
FIGURE 5.4: Mean Pardé curves for all stations within the same cluster. The three colors indicate different time periods.

year than in the past. The smallest relative changes were found for stations within the 'Plateau' cluster. There is a tendency for the discharge to decrease in (late) autumn and increase somewhat in spring. However, the changes are only marginal, so that the amplitude of all three time periods remains between 0.8-1.3. The situation is different in the group 'Alps'. The biggest changes have occurred between the first and second periods; especially in midsummer, the relative proportion to the annual runoff has dropped, but it has noticeably increased in the cold half of the year. This increase during periods of low runoff, and the simultaneous reduction at peak times, have made the amplitude much more balanced over the year. Comparable changes, but not as pronounced, are also observed at stations of the 'High-Alps'. However, the largest decrease of the Pardé coefficient over the summer months occurred here between the second and third periods. It is characterized by slightly higher runoff in spring and early summer. Whereas the average Pardé maximum value was around 2.9 at the beginning, it decreased to around 2.7. Winter discharges, on the other hand, have not changed noticeably. On the southern side of the Alps, the changes look somewhat different. The typical two-hills-shape still exists, but the first peak tends to be earlier in the year (shifted from June to May) and also less pronounced (both the minimum and the maximum value). The second peak at the beginning of winter, on the other hand, has become stronger and also tends to occur somewhat later.

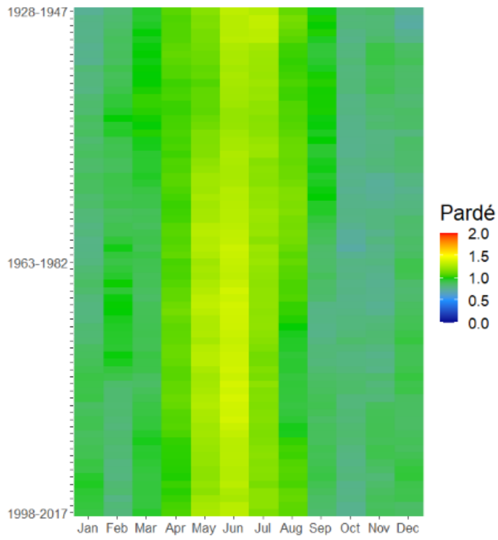
In addition to these fundamental changes, we performed the same evaluation with a higher level of detail. Our goal was to show a constant temporal evolution, where each time step corresponds to a 20-year mean constantly shifted by one year at the time. Using six selected stations (one per cluster), we try to explain the trends of the regime changes in more detail (Figure 5.5). If we look at Figure 5.5a, we can see the course of a typical station in 'Jura' described above. The summer months tend to be drier compared to the annual mean, but the discharges of the winter months December and January have increased. It is additionally noticeable that many months have not either only increasing or only decreasing tendencies. For example, the Pardé coefficient first increased in April (until about 1970-1989) before decreasing afterward. Furthermore, a shift of the peak (between April and March) can be noticed. The example station of the 'Large catchment' group shows much more constant changes, and fluctuations of rising and falling are not observed. The trend towards summers with lower discharges but higher discharges in the cold half of the year is visible. As already mentioned, stations of the 'Plateau' are subject to the smallest changes. Using the example of the Brugg station, no significant changes were found, with just a slight shift of the maximum value towards earlier months. More significant changes occur at stations within the 'Alps', as shown by the example of Ilanz (5.5d). At the beginning of the data series, a much higher intra-annual variation of the discharge can be observed. With



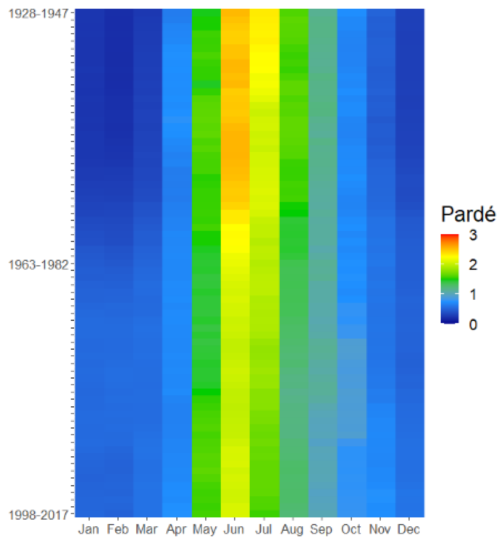
(A) Jura - Boundry



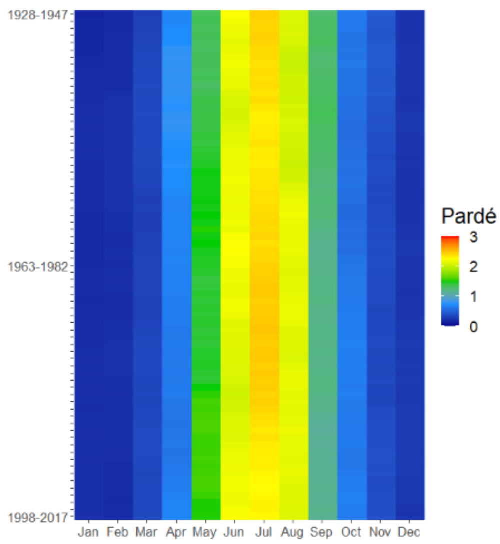
(B) Large catchment - Neuhausen



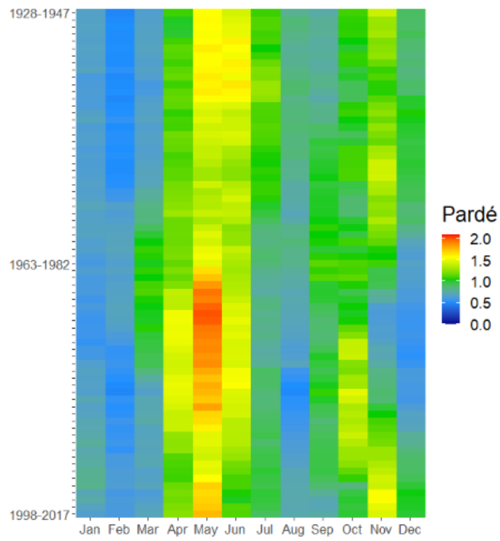
(C) Plateau - Brugg



(D) Alps - Illanz



(E) High-Alps - Gsteig



(F) Southern Alps - Ponte Tresa

FIGURE 5.5: Time variation of the Pardé coefficient using a moving 20-year window (1928-2017). Note the different color schemes.

time, this difference between high summer discharge and rather dry winter has leveled out somewhat. A temporal shift of the maximum discharge cannot be identified for this station in particular. The station Gsteig ('High-Alps') shows a comparable trend, but the significant changes do not occur at the beginning of the observed period but in the second half. There are almost no changes during the winter months. The typical picture of the 'Southern Alps' with the two-hills shape is also visible in Figure 5.5f (although there is a lake regulation system). The most considerable changes concern the first peak, where also here first an intensification of the amplitude and later a weakening can be observed. The second peak remains relatively constant in terms of amplitude, but there is a particular temporal shift.
The observed changes can partly be attributed to a changing climate (precipitation, temperature); conversely, direct anthropogenic factors also have a decisive influence.

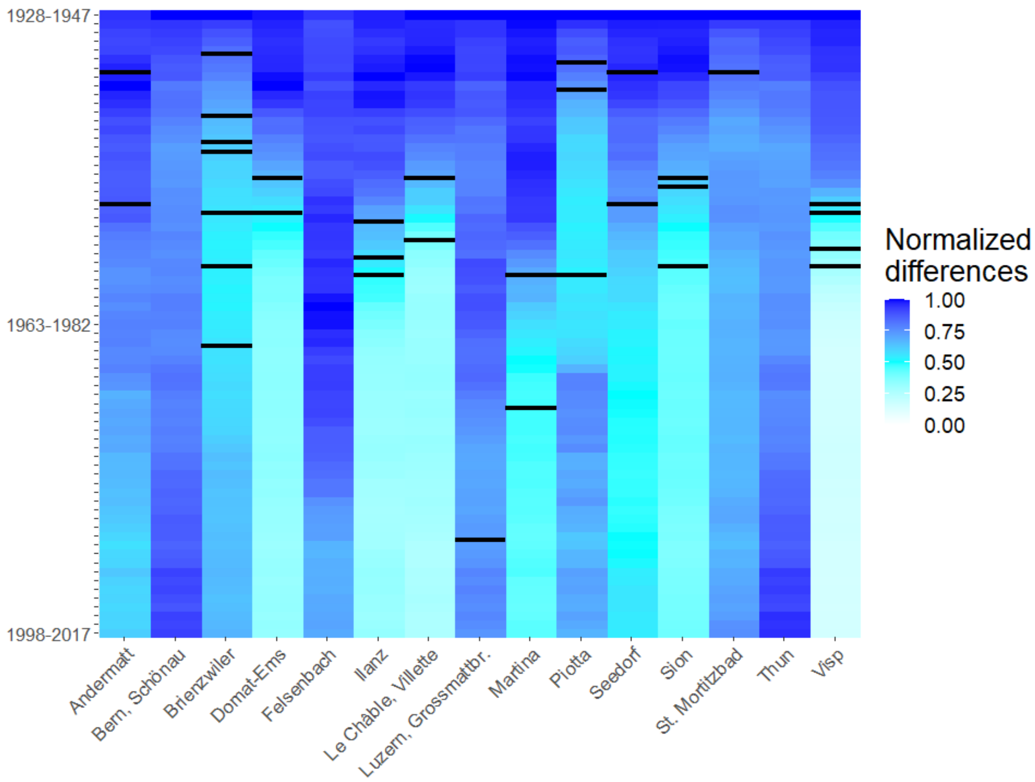


FIGURE 5.6: Detailed plot of the normalized ratio between the month with the highest and the month with the lowest Pardé coefficients for all stations of the 'Alps'. The y-axis represents a 20-year window, which is shifted by one year for each step down (top row represents the average value of 1928-1947, the next row 1929-1948, ...). Thus, the normalized values represent the amplitude variation of Pardé values in a year, with low values describing a more balanced flow regime and 1 the year with the strongest variation. The black horizontal lines indicate important structural changes in the respective catchment (detailed listing of these influences can be found in Table A.1).

Thus, the construction of dams and hydropower plants leads to a more balanced discharge throughout the year. Figure 5.6 shows this based on all 15 stations of the region 'Alps'. The y-axis represents the same 20-year regime windows as before. Shown in color is the normalized difference between the month with the lowest and the month with the highest Pardé coefficient. 1 indicates that this period has the greatest within-year runoff variability; the lower the value, the more balanced the runoff. The black lines show significant anthropogenic influences, such as the construction of hydroelectric power plants or dams.
On the one hand, we see that one or more constructional measures influence practically all catchments. At almost all stations with such constructions, the discharge variability has changed significantly afterward. This off-leveling of the regime over the years can be seen particularly clearly at the stations in Visp or Ilanz. According to the FOEN, only the stations Bern-Schönau, Felsenbach and Thun have not experienced any significant structural influences in their inflows (at least for the observed period). These are the stations that have experienced the least regime changes over time. A detailed description of all structural measures is summarized in Table A.1 (see appendix).

5.1.4 Extreme year

The runoff volume between individual years varies depending on weather conditions and the characteristics of the catchment area. Of particular importance are years with very low runoff, as they can have large impacts on different sectors such as agriculture or electricity production. We wanted to find out how well the spatial distribution of an extreme year correlates with the cluster areas. For this purpose, we calculated the annual runoff volumes for all stations and determined the year that carried the lowest volume. To minimize the influence of possible storage changes in snow and ice, we made the evaluations based on the hydrological rather than the calendar year. In

Table 5.1: Number of stations with the lowest annual discharge by cluster and extreme year. The value in the bracket indicates the relative proportion of stations within a cluster, with a high percentage representing a good spatial correlation between cluster and extreme year. Cluster 1 = 'Jura', 2 = 'Large catchment', 3 = 'Plateau', 4 = 'Alps', 5 = 'High-Alps', 6 = 'Southern Alps'

Cluster	1992	1996	1998	2006	2011	2017	other
1	3 (9%)	3 (9%)	2 (6%)	0	11 (32%)	15 (44%)	0
2	0	1 (4%)	8 (32%)	1 (4%)	15 (60%)	0	1 (4%)
3	9 (23%)	1 (3%)	15 (38%)	0	10 (26%)	2 (5%)	2 (5%)
4	0	8 (23%)	0	6 (17%)	9 (26%)	0	12 (34%)
5	0	5 (50%)	0	0	1 (10%)	0	4 (40%)
6	0	0	0	5 (63%)	0	0	3 (37%)
Total	12	18	25	12	46	17	22

Switzerland, the hydrological year begins on October 1 and lasts until September 30 of the following year (subsequent years refer to the year in which the hydrological year ends. Example: 1992 (October 1, 1991 - September 30, 1992)). About 85 % of all stations show the lowest discharge in one of the six years highlighted in color (5.7). If we look at the spatial distribution of individual years, we detect certain clusters of the same years in a certain region. It is also noticeable that these regions often coincide with the cluster boundaries, respectively stations with the same regime behave similarly. It is evident for the year 2006, which mainly affected the areas south of the Alps, or 2017, which measured low discharges in the Jura region. Table 5.1 shows these correlations between cluster and extreme years.

2011 was the year with the most affected stations (46) in the 30 years studied. Especially stations of the 'Large catchment' group were affected, but also large parts of western Switzerland and the Pre-Alps. While in 1998, especially central and northwestern Switzerland had low discharges, the year 1992 was drier than average in eastern Switzerland. The already mentioned year 2006 was extreme on the southern side of the Alps and in the southern Alps, but with one exception, there are no stations north of the Alps. Stations in the Alpine regions ('Alps' and 'High-Alps') are less well covered than the other clusters. Most of them can be assigned to the year 1996.

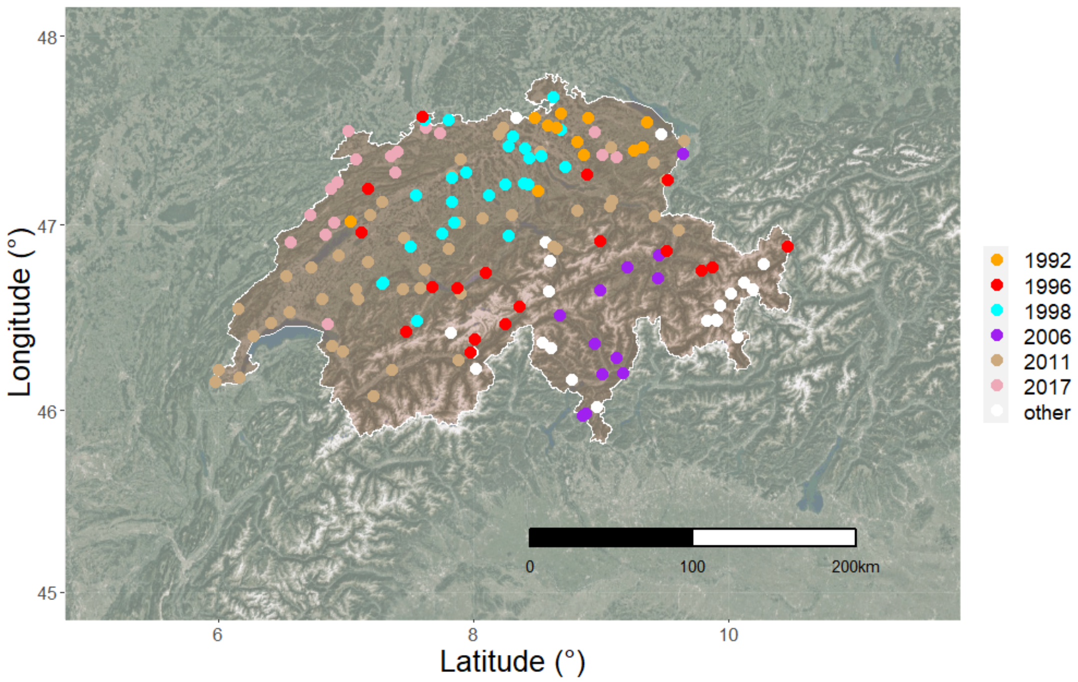


FIGURE 5.7: Spatial distribution of hydrological extreme years (hydrological year with the lowest discharge). The six most often years were selected.

5.1.5 Duration and magnitude of low flow events

Different hydrological variables can quantify a low flow event. Two of the most important are duration and magnitude. The duration determines the number of days on which a certain discharge threshold value is not exceeded. A common parameter is, for example, the Q347 value (i.e., the discharge value that is exceeded on 347 days per year, often also referred to as the 95% percentile). We used this approach for our analysis. Instead of determining a new percentile for each year, we calculated the 95% percentile of the analyzed 30-year period (1988-2017), so the number of days below the threshold is not constant for all years. The second variable is the magnitude. It measures the severity of a low water event and quantifies the extremeness of the low flow. To compare low water events of different years, a combined approach of these two variables is necessary. The combination of duration and magnitude describes the severity of an event (i.e., the discharge deficit). The deficit of a short but extreme low flow event can be the same as a long-term low flow with a less pronounced magnitude. Figure 5.8 shows the duration and the magnitude of low flow events for the 30 years by clusters. The column height represents the number of days below the 30-year threshold,

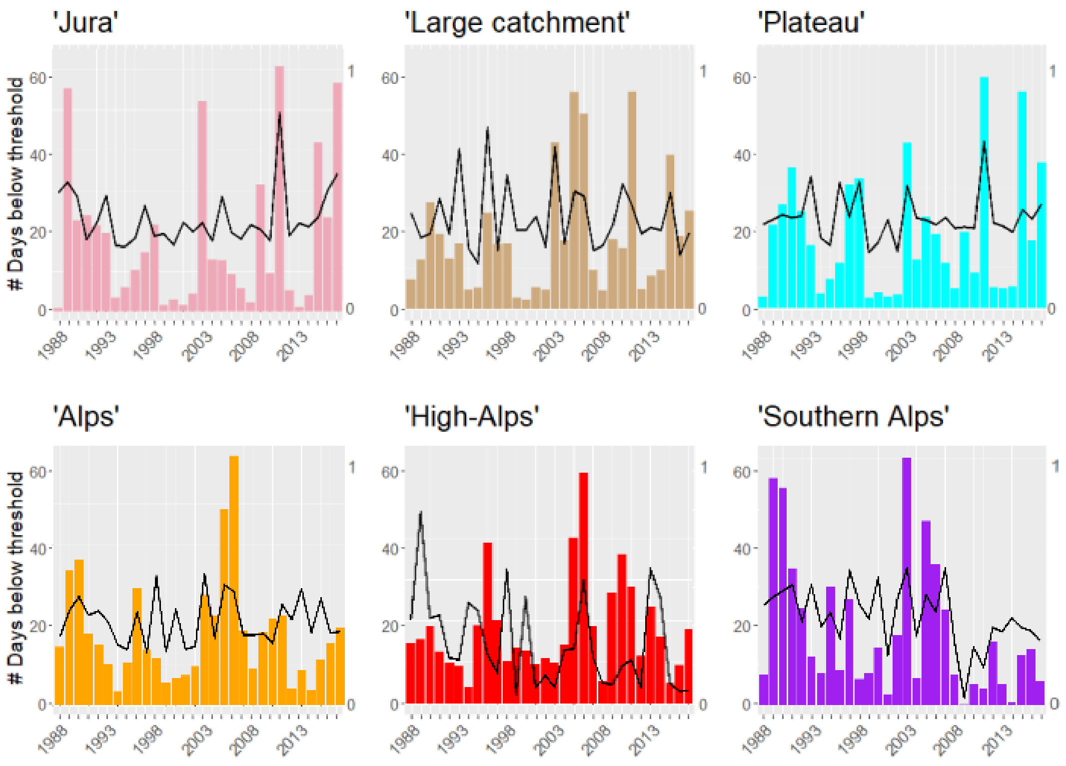


FIGURE 5.8: Number of days with a discharge smaller than the long-term 95 % quantile (left y-axis). The black curve shows the normalized average magnitude of those low water days (right y-axis). The represented values were calculated using the mean values of all stations within a cluster.

and the black line represents the normalized magnitude of those days (second y-axis). We first calculated the maximum magnitude of those 30 years for each station and then normalized it over the entire period for the magnitude calculation. The figures show the average of all stations of a cluster and therefore have maximum values below 1. These plots allow us to compare the different low flows between different years within a cluster. For stations north of the Alps ('Jura', 'Plateau', and 'Large catchment'), most days below the long-term threshold were registered for 2011. The years 2003, 2015, and 2017 are also years in which many days were below the threshold. Considering the normalized magnitude, a high value can be seen especially for the regions 'Plateau' and 'Jura' in 2011. It is not necessarily true for the catchments of the 'Large catchment'. These data thus show that the year 2011 in these three regions had a below-average runoff on a huge number of days, but that the severity varied within these regions. We can detect the opposite for the year 2003. That year was also particularly dry in terms of the number of days below the threshold but extreme in magnitude, especially in the 'Large catchment' region. In summary, a stronger correlation of high magnitude values with a high number of days can be observed in the regions 'Plateau' and 'Jura' than 'Large catchment'. The picture is quite different for the Alpine region ('Alps'

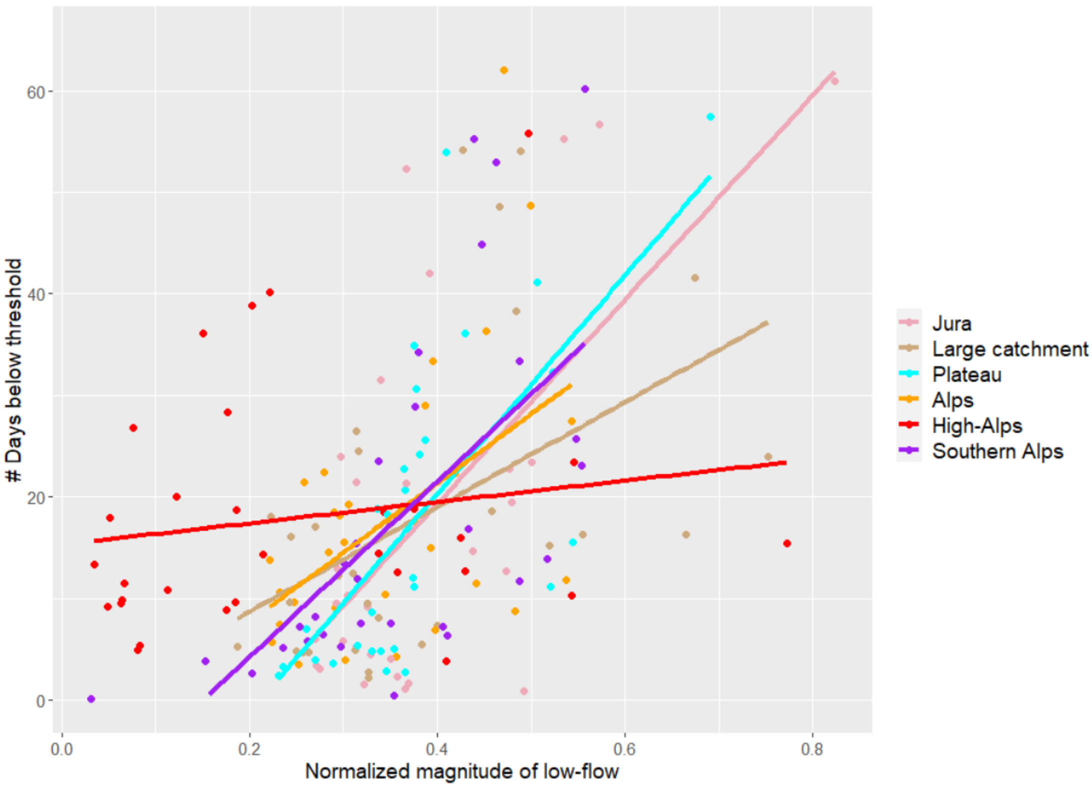


FIGURE 5.9: Correlation of the duration and the magnitude of a low flow event. The trend of each cluster is showed by a line. Each point represent an event with a below 95%-Quantile discharge.

and 'High-Alps'). The year with most discharges below the threshold for both regions was 2006, followed by 2005. Other extreme years were 1996/2010 ('High-Alps') and 1989/1990 ('Alps'). The normalized magnitude does not show significant fluctuations, especially for 'Alps', and is therefore not exceptionally high for any of the extreme years. For the 'High-Alps', the amplitude is more prominent but constantly at a lower level than the rest of the regions. Again, no clear correlation between the number of days below the threshold and the magnitude is evident. The stations of the 'Southern Alps' show a somewhat mixed pattern. The most extreme year in terms of the number of days below the threshold is 2003, similar to the stations north of the Alps. Other extreme years are 1989/1990 and 2005, comparable to the 'Alps'. For the magnitude, the pattern is also unclear, and a significant correlation between the number of days and the severity of the low flow is not given.
Figure 5.9 summarizes the correlations just described. Whereby the correlations are especially given for 'Jura' and 'Plateau'. In these two regions, the magnitude seems to be stronger related to the length of the low flow event compared to e.g., the 'High-Alps'. Based on this plot, we can assume that the magnitude and the severity (runoff deficit) of a low flow event are highly dependent on the region in which it occurs.

5.1.6 Minimum 7-day discharge

The previous sections have shown that a separation between the different regions is essential and that the output of a given hydrological variable depends strongly on the spatial location of the catchment. As highlighted above, some years indicate dry conditions for one region but less extreme for other regions. It is also true for the analysis of a minimum 7-day runoff. Here we focus on the characteristics of clusters as a whole rather than individual catchments. Therefore, the following figures represent the median return period for all stations within a cluster. The median was chosen because the mean is more susceptible to outliers, and one high return period could strongly influence the entire data.

Plot 5.10 allows us to determine which months were dry, especially to compare different extreme years. The top-left Figure of 5.10 shows the table for 'Jura'. There are some years with darker colors than others. The most extreme years are 1989, 2003, 2011, and 2017, which is consistent with the duration of low runoff (Figure 5.8). Within these years, there are different patterns. While 1989 and 2003 were particularly dry in the second half of the year, this was true for 2011 in the first half. Then 2017 is again more spectacular with quite dry months throughout the year. The months with mean return periods higher than 500 years were determined for July/August 2003, May 2011, and the turn of 2016. In general, most months have return periods of less than

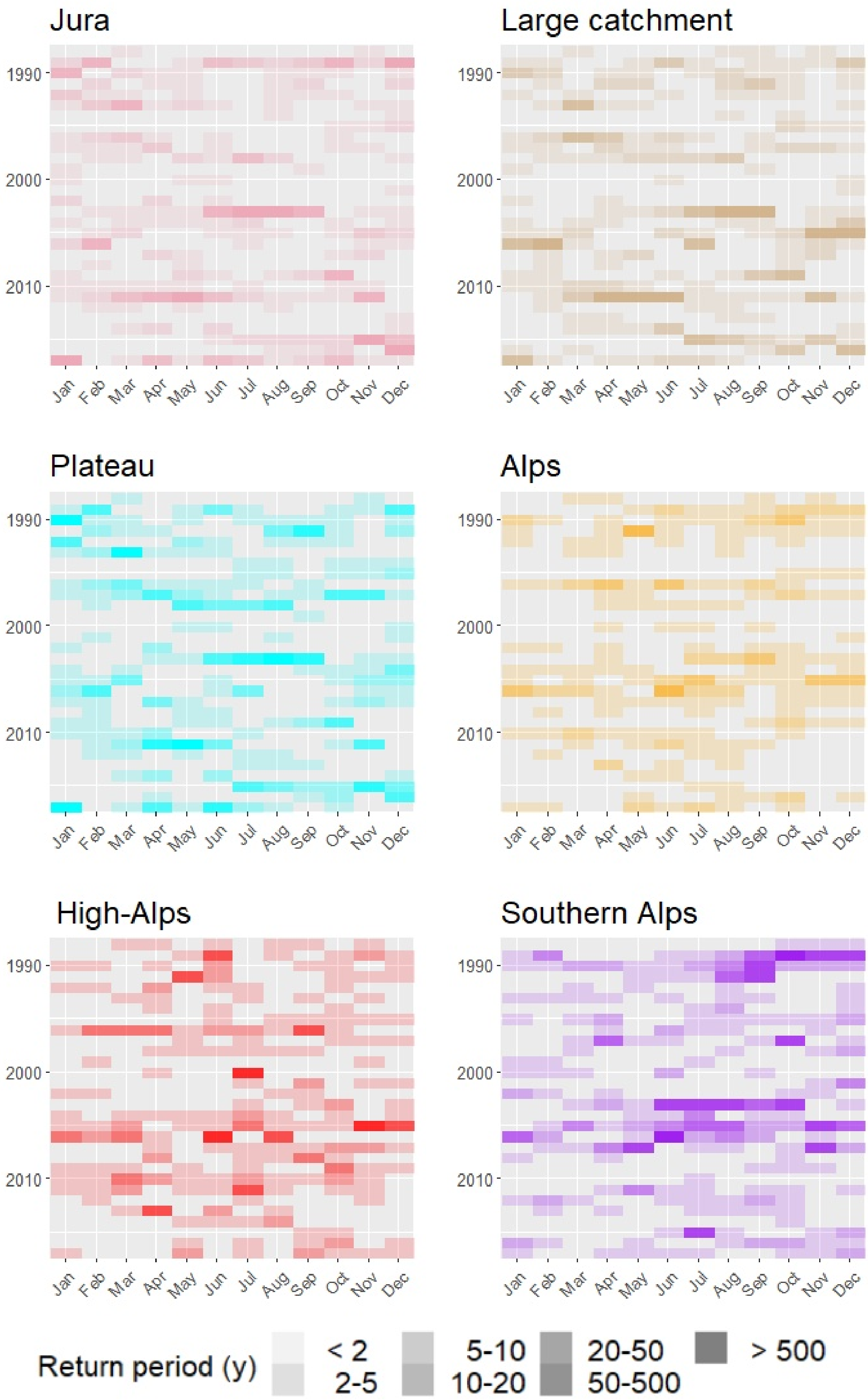


FIGURE 5.10: Median return period of the lowest 7-day discharge of all catchments within a cluster. The color brightness describes the intensity of an event.

two years. 'Large catchments' have roughly the same general characteristics with only a few other expressions. For example, the late 2005/early 2006 period has a slightly higher return period than 'Jura,' and 2015 is also slightly more pronounced. On the other hand, 2017 was not as extreme as 'Jura'. The results for the 'Plateau' region are also very comparable to those already mentioned. However, significant differences to the three clusters north of the Alps are found at stations in the Alpine region. Thus, median values of the return period of more than 50 years do not occur at any single month. The values are not only generally lower but also clearly differentiated in time. The months with the highest return periods are in the years 1991, 2005, and 2006. Again, quite well compared with the representation of the number of days with low water discharges. It is also noticeable that long periods (several months in a row) with extremely low water discharge hardly occur. We can observe something similar within the 'High-Alps'. In contrast to 'Alps', return periods of up to 500 years occasionally occur here. The years with a pronounced return period are 1996, 2005, and 2006, although we cannot link them to a specific season, as we did for the first clusters. Finally, the catchment areas south of the Alps are considered. Compared to Alpine stations, these show again more often higher return periods. The highest values are generally registered in the second half of the year. Years with particularly high median elevations in this region are 1989, 2003, and 2005.
Interestingly, we cannot highlight individual months or seasons that are often characterized by high return periods and would thus be decisive for a dry year. Instead, these illustrations have shown that extreme events with high return periods can occur occasionally.

5.2 Greater Alpine Region

We have more stations for the Greater Alpine Region, but their available time series is usually shorter than those within Switzerland. Therefore, we have been able to carry out our long-term evaluations ('Discharge trend' and 'Pardé change') only for a 50-year time series. For the remaining analyses, 'Extreme year', 'Minimum 7-day discharge' and the 'Low flow analysis, we determined a period of 30 years again as we did with the Swiss data.

5.2.1 Discharge contribution

Again, we calculated the discharge contributions by clusters. Since we followed the same structure for the clustering as in the previous chapter, the outcome looks similar.

Therefore, we decided to discuss a slightly different representation (for the sake of completeness, the missing barplot can be found in A.2). Figure 5.11 shows a correlation matrix with plots of all four contribution classes plotted against each other. This plot, unlike the boxplot, visualizes each station and thus allows the variability within a cluster to be observed. In almost all subfigures, we can see clustering by colors. Especially the catchments of 'High-Alps' stand out quite significantly from the other stations in most cases. The intermediate and long-delay contributions are exceptionally high, with a cluster of data points in the range of 50 % and one in the range of about 20 %, respectively. It shows that significant differences occur between the individual stations within' High-Alps', especially for intermediate and long-delayed contributions. The group of 'Alps' stations is also characterized by rather high proportions of intermediate and long-delayed contributions, although not quite as pronounced as the ones in 'High-Alps'. If we compare stations from 'Large catchment' with those from 'Plateau', we detect a similar behavior, although 'Plateau' has slightly higher short-delay values for somewhat lower proportions of baseflow. Catchments in the 'Jura' region tend to

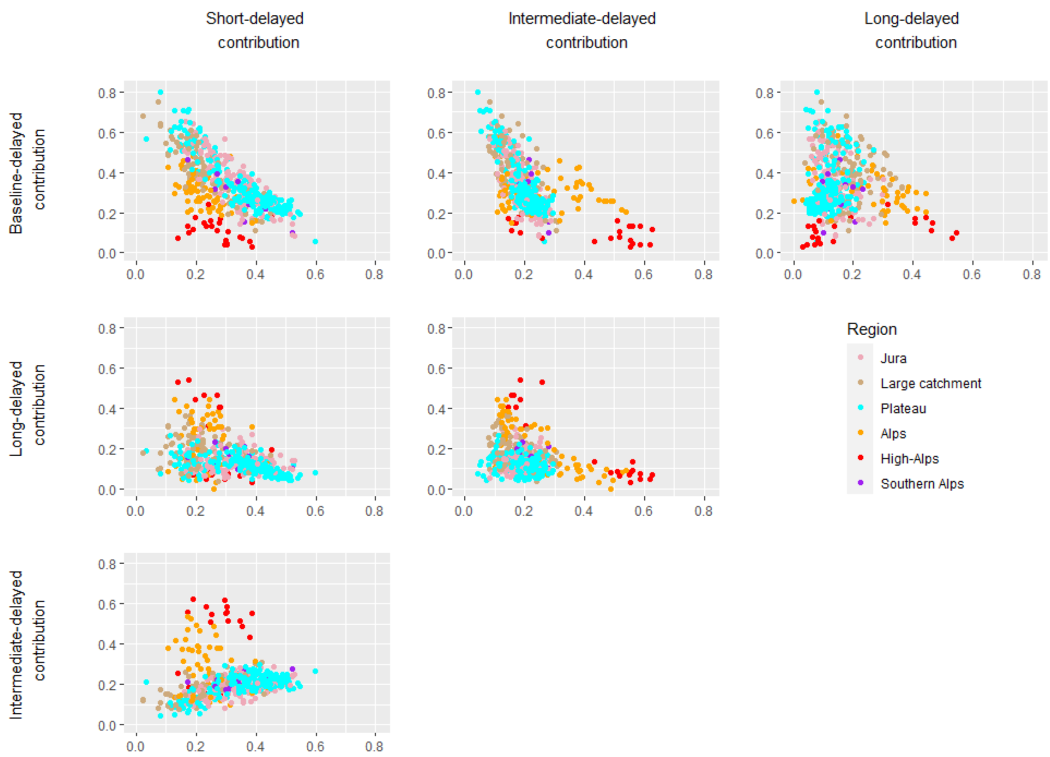


FIGURE 5.11: Correlation matrix between short (left), intermediate (middle) and long-delayed contribution (right) against baseline (top row), long (middle row) and intermediate-delayed contribution (bottom row). Each point represents a station and is colored according to its cluster.

have higher baseline contributions than the rest but lower contributions of intermediate and long-delayed flow. Stations south of the Alps are small in number, but they are all rather close to each other so that no large differences between stations within this cluster are obvious. Their character is most comparable to that of the 'Plateau'.

5.2.2 Long-term discharge trend

Compared to the evaluation of the Swiss stations, we have significantly more catchments in every cluster. In total, 285/527 stations have runoff data for the period 1961-2010. Again, we have the least data for the regions 'High-Alps'(19) and 'Southern Alps'(6) and the most for 'Jura' (79) and 'Plateau' (76). The procedure is the same as for the evaluation of the Swiss stations in the previous section. The 79 stations of 'Jura' show large fluctuations between the individual years, and a visible trend is not apparent (Figure 5.12). Also, the increase in runoff volume of +0.33 %/dec is not statistically significant. The same is true for the cluster 'Large catchment', with large fluctuations but no clear trend. However, compared to the first cluster, a decreasing rather than an increasing trend can be observed (-0.48 %/dec). The 'Plateau' cluster

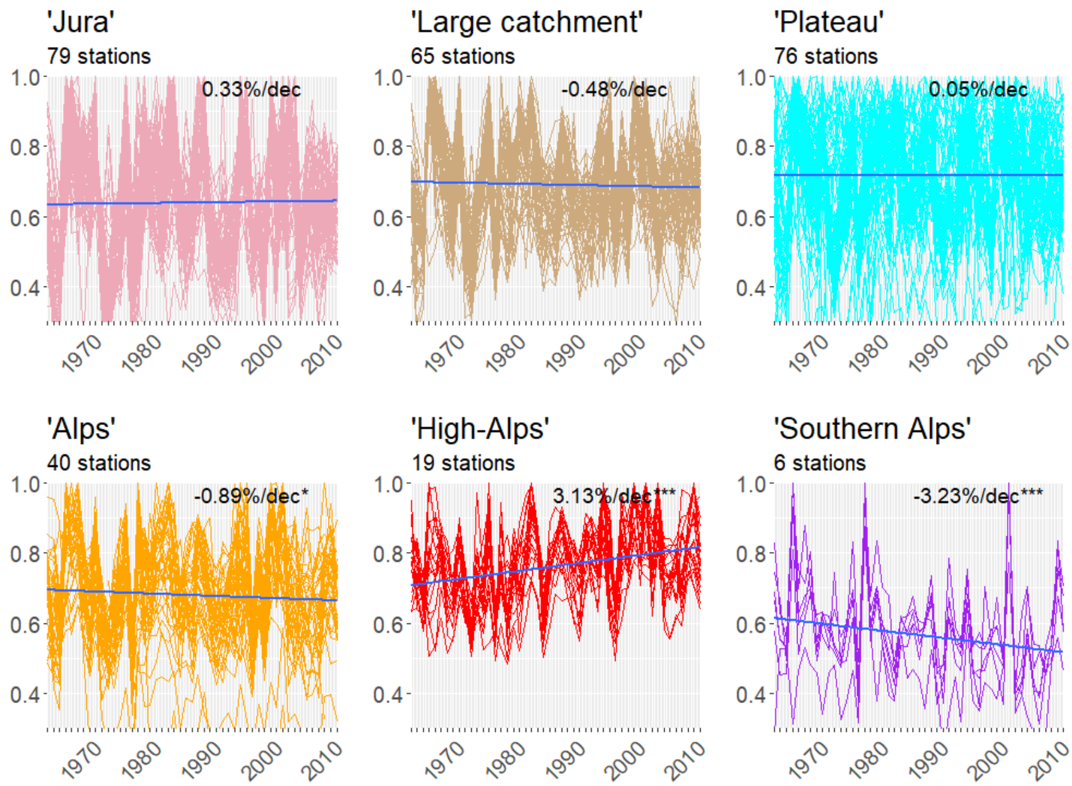


FIGURE 5.12: Same as Figure 5.2 but for stations of the GAR. Note the different periods on the x-axis (1961-2010).

stations show practically no change in discharge over the observed 50 years. What is particularly striking here is the strong variability of individual stations. Unlike the other clusters, no "wave-like" behavior is evident here. A slightly statistically significant decrease of the annual discharge of about -0.9 %/dec can be found at stations within 'Alps'. Furthermore, the individual outlier curves towards the bottom are noticeable, which partly fall below 30 % of the normalized maximum value (0.3 on the y-axis). The course of the 19 stations within 'High-Alps' shows a highly significant trend ($p < 0.001$). The runoff increased on average by +3.13 %/dec. Moreover, this appears to be true for all stations within this cluster. The opposite can be observed for the stations on the southern side of the Alps. Although only six stations were available, the decreasing trend of -3.23 %/dec is strongly significant, and the curves of all stations are quite comparable.

Figure 5.13 shows in more detail the seasonal discharge trends by region. During winter, discharges have generally increased in all regions. The increase is most significant in the High Alps (+3.86 %/dec) and for stations south of the Alps (+2.98 %/dec). The increasing trend is weakest for the 'Plateau' (+0.55 %/dec). Statistically speaking, the changes are most evident within 'High-Alps' and 'Large catchment'. Spring is the season with the largest differences between clusters. While the runoff of the 'High-Alps'

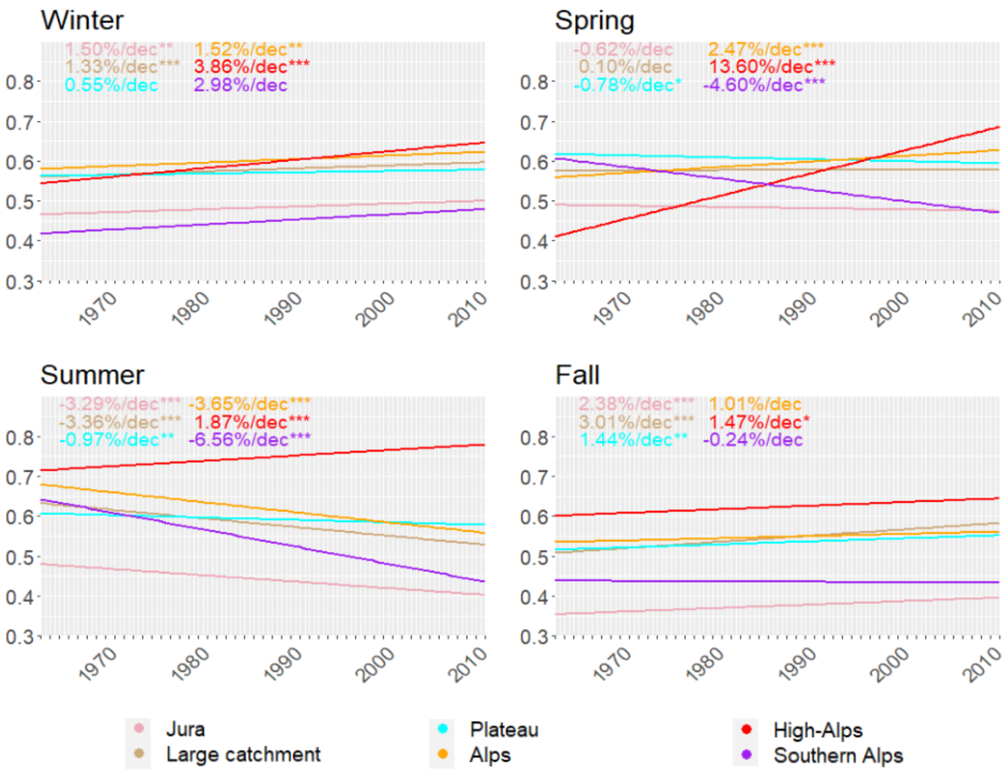


FIGURE 5.13: Same as Figure 5.3. Note the different time period on the x-axis (1961-2010).

FIGURE 5.14: Same as Figure 5.4. Note the time periods are different, so that the first time period corresponds to the second period of Figure 5.4.

catchments increased by 13.6 % per decade, the runoff volume of the 'Southern Alps' stations decreased significantly by -4.6 %/dec. Likewise, we found a significant increase in the runoff for stations in the 'Alps'. For the remaining three clusters north of the Alps, the changes were only marginal and often of decreasing nature. For summer runoff, the changes are highly significant for all regions ($p < 0.001$, except 'Plateau' with $p < 0.05$). Discharges decreased in all areas between 1-6 %/dec. The only exceptions are the 'High-Alps' catchments, which even registered discharge increases of about 2 %/dec. The runoff trends in fall are mostly increasing. These changes are particularly significant in 'Jura' (+2.38 %/dec) and for 'Large catchment' (+3.01 %/dec). Only the 'Southern Alps' stations show slightly lower discharges over time, although these changes are not significant.

5.2.3 Pardé change

The Pardé change evaluations are again based on the 50-year time series of the 285 stations. The shown curves represent the average regime of the time periods 1961-1980 (green), 1976-1995 (black), and 1991-2010 (blue) (Figure 5.14). For the 'Jura' region,

the largest changes occur in the first half of the year. While the discharge contribution in the first quarter increased, it decreased in the following months, resulting in a constant lower Pardé coefficient until summer. In autumn, there were rather few changes, but a slight tendency for the runoff to increase. For the stations of the cluster 'Large catchment', the changes occurred especially in the second half of the year. While the discharge tended to decrease in (early) summer, it increased in autumn and winter. The Pardé coefficients have shifted by about 0.2 each. The amplitude has decreased slightly over the 50 years so that the discharge became more constant. The 'Plateau' has the most balanced regime, and changes over time are also not very pronounced. The small changes show slightly lower runoff contributions in the first half of the year but slight increases in the second half. The amplitude has not changed significantly. At the stations 'Alps', on the other hand, we can find a clear trend. The peak values in the summer months of June-August constantly decreased. The "missing" contribution of the summer runoff has shifted mainly to the beginning of winter so that the Pardé coefficients have increased by about 0.2 points between October and December. A more differentiated course of the Pardé coefficient is shown for the 'High-Alps'. The second period shows a stronger annual cycle than the first one, with a higher proportion of runoff in July. However, if we consider the third period, we see the opposite trend, so that this curve is even less pronounced than the first one. A large fraction of the runoff has shifted towards the spring, with practically no changes in the runoff contribution in the winter months. There has been a tendency for the amplitude to decrease recently. Similar development regarding the first peak can be seen for catchments of the 'Southern Alps'. First, an increase of the runoff contribution, then an even larger decrease. The behavior of the second peak is contrary because it seems to have become more pronounced. Based on our evaluations, the typical representation of a stronger first peak is no longer given.
We also conducted a detailed evaluation of individual sample stations for this study region (comparable with Figure 5.5). The corresponding figures can be found in Appendix A.3.

5.2.4 Extreme year

For the extreme year analysis, we used runoff data of the period 1982-2011, where the year refers to the hydrological runoff year. The spatially represented years are the same as for the analysis within Switzerland (except for 2017, where we do not have sufficient data). Over half of all 527 stations recorded the lowest annual discharge for one of the highlighted years (1992, 1996, 1998, 2006, and 2011). The spatial representation of the distribution patterns of the individual low flow years indicates some correlations

(Figure 5.15). The year 1992 was particularly low in discharge in the eastern Plateau region of Switzerland and the northernmost parts of the GAR (Thuringia region). Four years later, the focus of low flows was in large parts of the (pre)Alps and the French Jura. In 1998, on the other hand, the low-elevated stations of the western Central Plateau (Switzerland) and many German stations measured low annual discharges. Of the five years highlighted in colors, 2006 is the one with the smallest number of stations. However, this is relativized if the spatial distribution is considered. Apart from a few catchments in Germany, stations south of the Alps were particularly affected that year, which were only weak covered by our data set. The last year of the study period is also the one with the most stations (99 stations for the year 2011). The spatial pattern extends from the French Jura over large parts of western Switzerland to Salzburg at the Austrian-German border. A detailed overview of the spatial distribution can be found in Table 5.2.

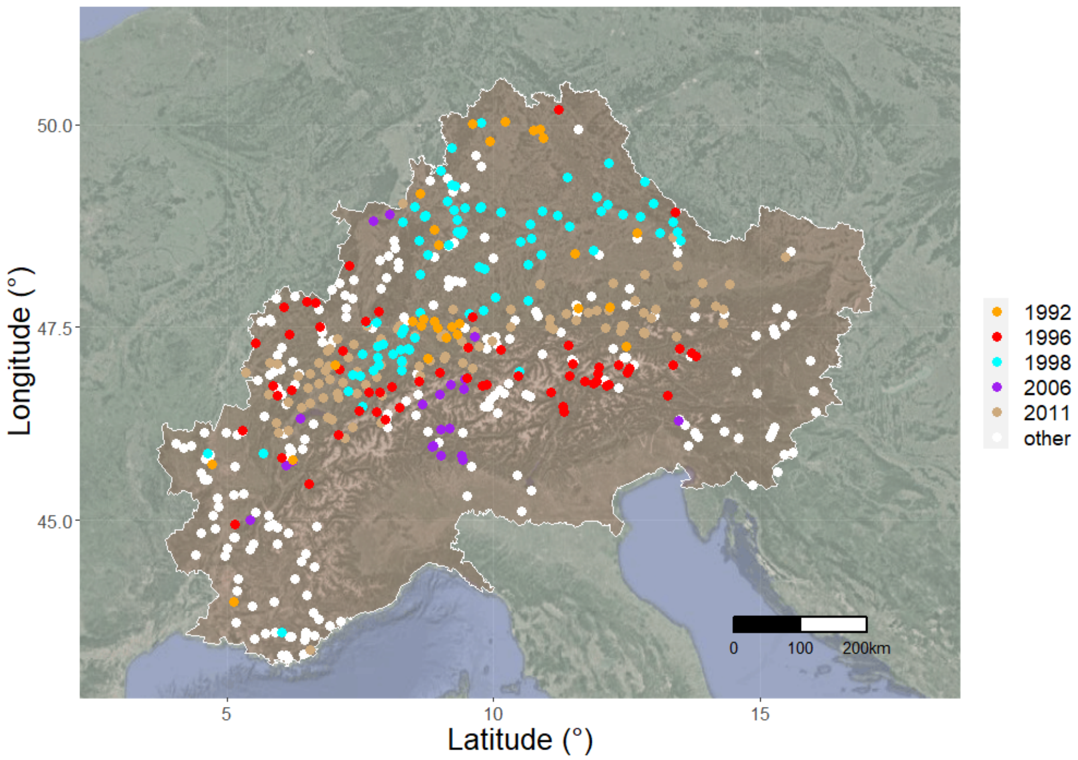


FIGURE 5.15: Same as Figure 5.7 but for the GAR.

Based on the two tables (5.1, 5.2), the results of the two study areas can be compared well. As already mentioned in the text above, the extreme individual years mostly occurred in distinct cluster regions. 1992, however, is the year where a spatial correlation with a cluster is least visible. While within Switzerland, it affects 23 % of all stations of the 'Plateau', it is only 8 % in the GAR. We have a much larger spatial correlation in 1996, where most of the stations with the lowest annual runoff are located in the Alps. About half of all 'High-Alps' stations registered the lowest discharge values in that year (Switzerland: 50 %, GAR: 48 %), but also the 'Alps' were particularly affected (Switzerland: 23 %, GAR: 31 %). The largest differences between the two study regions occurred in 1998. While in Switzerland, especially stations of the clusters 'Plateau' (38 %) and 'Large catchment' (32 %) had low discharges, within the GAR, these were the 'Jura' stations (26 %). The situation is more uniform for the years 2006 and 2011, where especially stations south of the Alps (2006; Switzerland: 63 %, GAR: 38 %) and those with a large catchment (2011; Switzerland: 60 %, GAR: 47 %) had particularly low annual discharges.

5.2.5 Minimum 7-day discharge

In the first part of the analysis of the return period of low water events, we decide not to give a detailed description of all six clusters of the GAR, as we did for the Swiss stations (corresponding representations can be found in Appendix A.4) but discuss a slightly different way of representation. In the second part, we will analyze the differences between Switzerland and the GAR. The following rank plots do not show the return periods of low flow events but rank individual years (and months) according to their average return periods within a cluster.

Figure 5.16 gives an overview of all clusters and shows how different the individual years were in terms of low flow events between the regions. Highlighted in colors are 1985 (blue - the year with the highest return period average across all clusters), 2003 (orange - extreme especially for low-elevated stations), and 1986 (red - high return values for Alpine stations). Although the blue curve represents the year with the highest average return periods, 1985 is never ranked first within individual clusters. The high ranking in the total thus comes from the fact that this year tends to be dry for

Table 5.2: Number of stations with the lowest annual discharge by cluster and extreme year. The value in the bracket indicates the relative proportion of stations within a cluster, with a high percentage representing a good spatial correlation between cluster and extreme year. Cluster 1 = 'Jura', 2 = 'Large catchment', 3 = 'Plateau', 4 = 'Alps', 5 = 'High-Alps', 6 = 'Southern Alps'

Cluster	1992	1996	1998	2006	2011	other
1	11 (8%)	12 (9%)	36 (26%)	2 (1%)	25 (18%)	54 (38%)
2	1 (1%)	6 (7%)	11 (12%)	3 (3%)	43 (47%)	27 (30%)
3	15 (8%)	9 (5%)	34 (17%)	4 (2%)	18 (9%)	116 (59%)
4	1 (2%)	20 (31%)	1 (2%)	6 (9%)	12 (19%)	24 (38%)
5	0	11 (48%)	0	0 (8%)	1 (4%)	11 (48%)
6	0	1 (8%)	0	5 (38%)	0	7 (54%)
Total	28	59	82	20	99	239

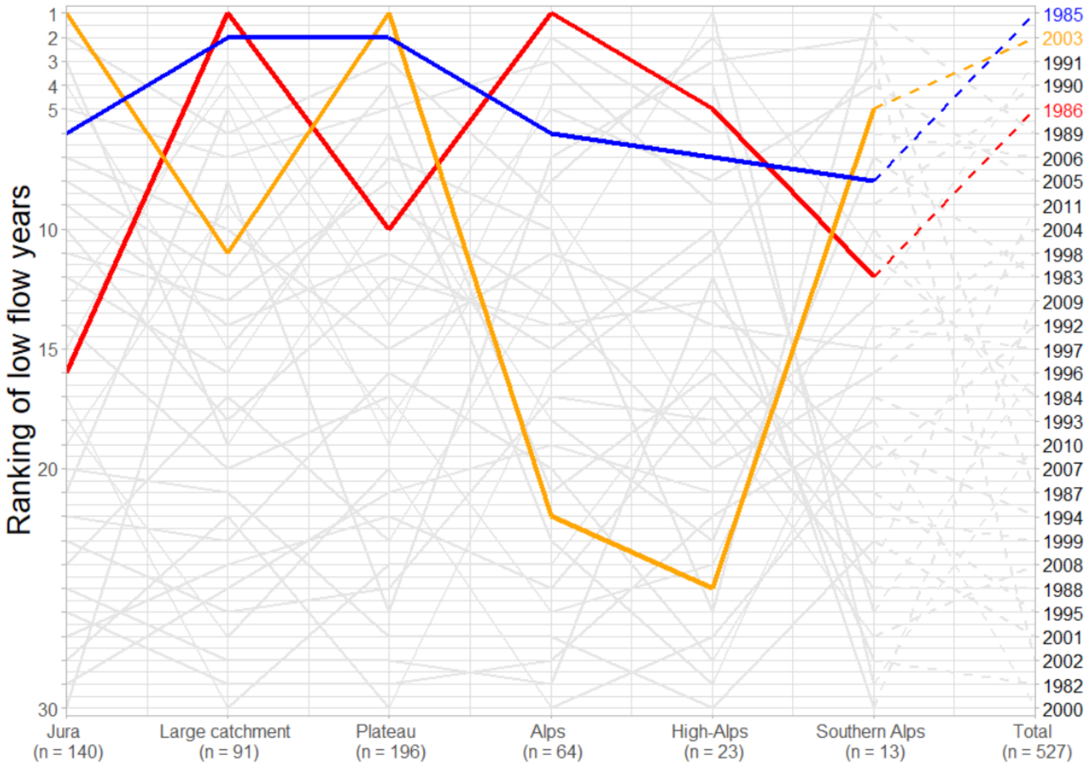


FIGURE 5.16: Ranking of the median return period of a minimum 7-day discharge event between the different years and clusters. If a year has a rank of 1, it means that no other year had higher return periods. In contrast, a rank of 30 means that all other years had more extreme return periods. Each line represents a year, with the years on the far right listed in descending order (the year with the highest average return period within all six clusters on top). The three years discussed are highlighted in color.

both Alpine and non-Alpine stations, with the effect being somewhat more pronounced on the northern side of the Alps. For all clusters, this year is in the top-8 most extreme years. The situation is somewhat different for the orange curve. It shows extreme low water events (for 'Jura' and 'Plateau' even the most extreme of all), especially at lower-altitude stations (northern and southern sides of the Alps). However, looking at the Alpine stations ('Alps' and 'High-Alps'), 2003 is not extreme for stations in these areas (rank 22 and 24 respectively). These regions are also the reason why 1985 and not 2003 is the most extreme year on average. Finally, 1985 is the year that is particularly dry for stations at higher elevations and stations representing large catchment areas. South and north of the Alps (especially in the 'Jura'), the average return period of the 7-day minimum discharge is roughly in the middle of all 30 years.

A monthly resolution of the average return periods for each cluster is shown in Figure 5.17. For the region 'Jura' the following characteristics can be identified. 2003 is, on average, the most extreme year because, especially in the summer months, the discharge is at a low level (even the lowest minimum 7-day discharge during the months

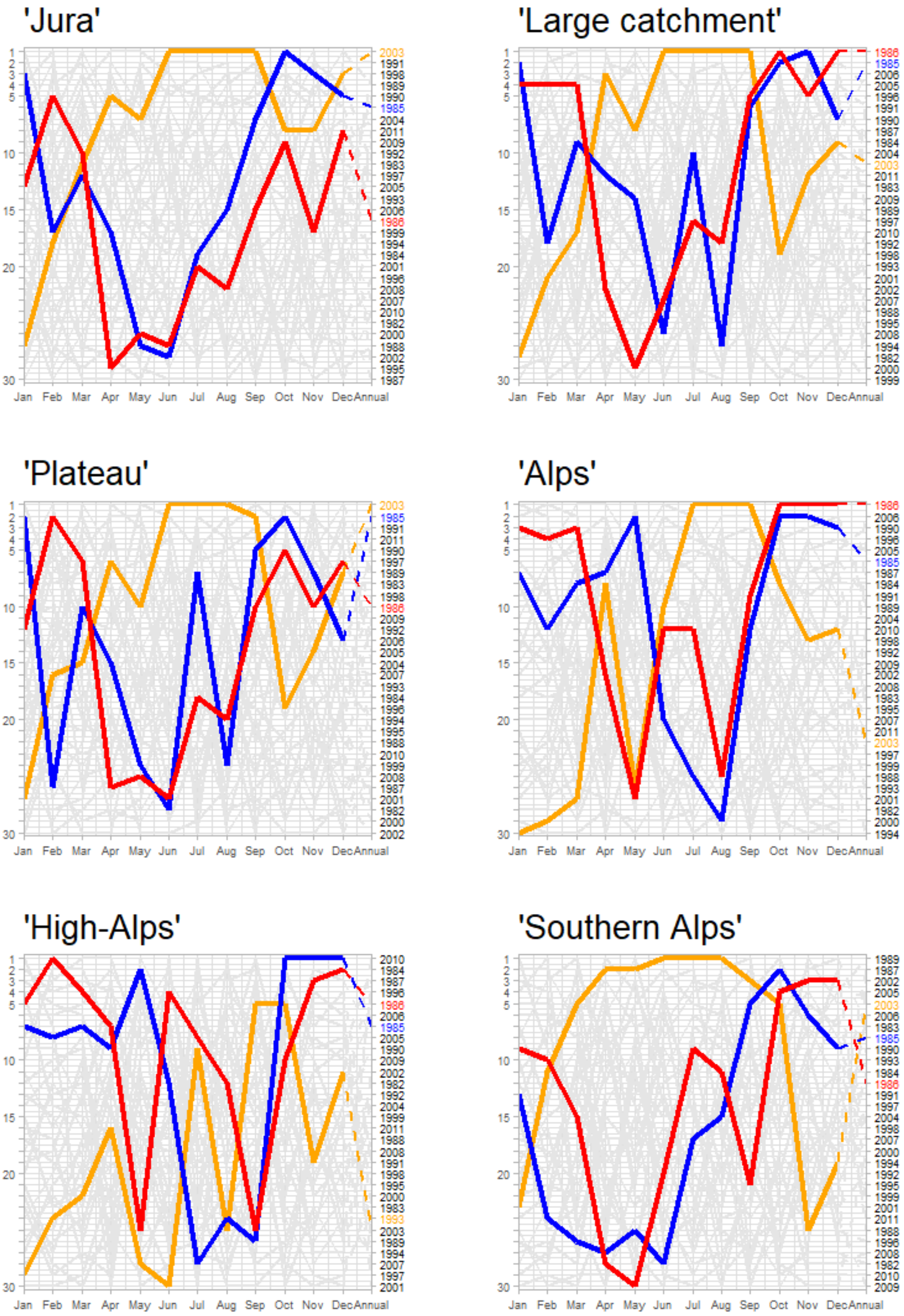


FIGURE 5.17: Same as Figure 5.16 but by cluster and month. The colored years are the same as in Figure 5.16.

June-September). Somewhat contrary to this is the first quarter, which has a relatively high minimum discharge. The years 1985 and 1986 can be compared very well because the cold half of the year has a low discharge, while the summer months, especially April-June, have relatively high values. 1985 is ranked somewhat higher because the low flow discharges in the second half of the year are still somewhat more pronounced. 'Large catchment' stations show a different pattern. Again, the summer months in 2003 are particularly dry, and the minimum 7-day discharge is low. Compared to the 'Jura', however, the discharge recovers much faster, so that the year in total is not the most extreme one. As before, the courses of the two years 1985/1986 are very similar. The winter months show consistently low discharges for both years so that in total the two years are ranked with the position 1 and 2. These characteristics are quite similar for stations within the 'Plateau'. Here the most extreme year is 2003, followed by 1985. The 'Alps' and the 'High-Alps' behave similarly, while some differences can be found for the year 2003, especially during the summer time. In general, however, it can be stated that the runoff in these two regions is more variable than in the other regions. At least for the three highlighted years, extreme years are predominately shaped during the winter months. Stations south of the Alps are somewhat of an exception. Here, none of the colored years is the most extreme year. However, 2003 was the year with the highest return periods of the minimum 7-day discharge from spring to summer. The curves for the years 1985/86 have some similarities with catchments north of the Alps.

A direct comparison for the two study regions is made for the period 1988-2011 and is shown in Figure 5.18. Months with bluish colors have higher return periods in the Swiss data set than the GAR data set, the opposite is true for the red colors. Focusing on the stations of the 'Southern Alps', significant differences of more than 100 years are found, especially for 1989, 2003, and 2011. Apart from these years, some minor differences are observed, with both red and blue colors having approximately the same contribution. When analyzing stations within the 'High Alps', only a few months differ by more than 20 years between the two data sets and are predominantly red-colored. Of all six cluster regions, 'Alps' shows the smallest differences between Switzerland and GAR. Almost no months are showing larger differences than five years. For the 'Plateau' stations, the return periods of the Swiss data set seem to be higher than the GAR, as there are many bluish colors. Similar to 'Southern Alps', the years 2003 and 2011 vary the most between the data sets. Small differences can also be found in 'Large catchment' in favor of lower return periods of the GAR. A comparable pattern arises in the 'Jura' region, with higher return periods in the Swiss data set, especially for 1989, 2003, and 2011.

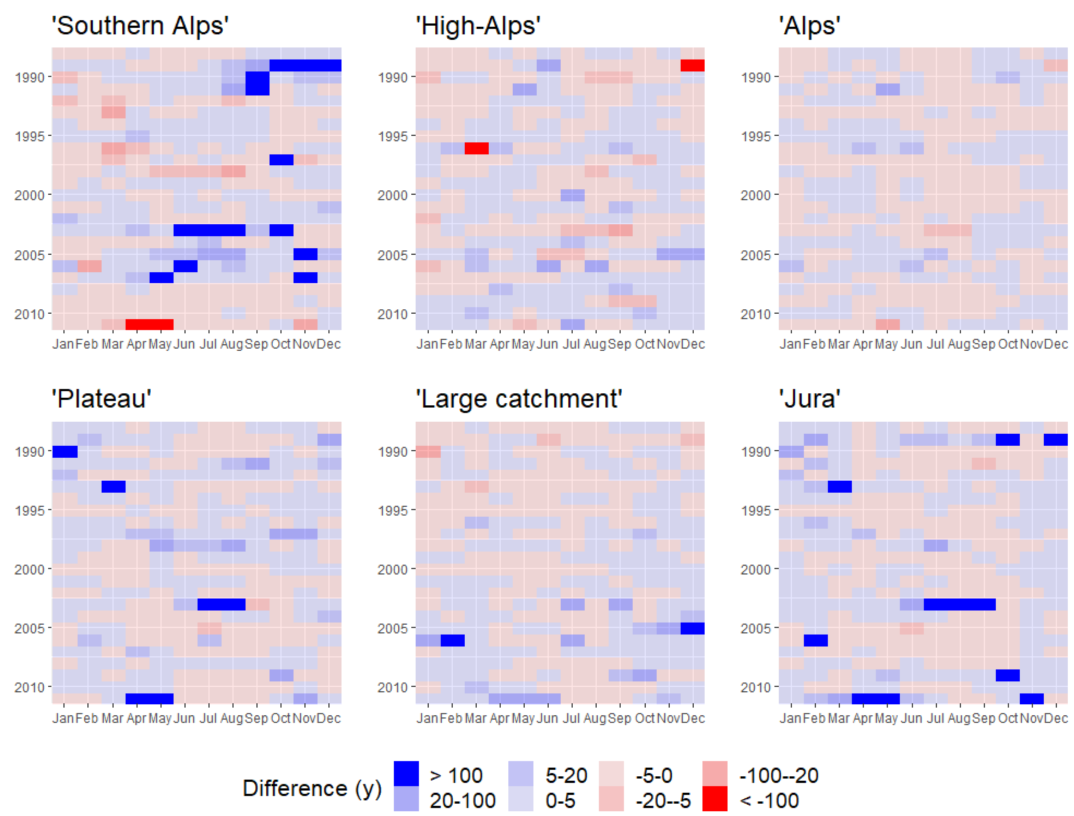


FIGURE 5.18: Difference of the minimum 7-day discharge return period between Switzerland and GAR. Blueish colors represent months with higher return periods for the Swiss data set, red colors correspond to higher return periods for stations within the GAR.

5.2.6 Low flow analysis

As an additional analysis, we searched for patterns when such minimum 7-day discharge events occur. For this reason, we calculated the mean start (day of the year) for all stations and plotted them against their elevations (Figure 5.19). We found a distinct shape that such low flow events occur earlier in the year for high-elevation stations (around February/March) compared with stations further downstream. Some low-elevation stations have their typical low flow event earlier in the year, but for most stations below 500 m a.s.l. Such events appear to start in the springtime (between March and July). There are no stations with their typical low flow event from September to December. The color of the points represents a second attribute. The color range goes from blue to red, blue representing stations with low variance and red ones with a larger one. Variance in this term is defined as the difference of the starting day between individual years of the 30-year reference period (1982-2011). In other words, blueish points represent stations where the starting day is roughly the same for all 30 years, whereas red points indicate stations whose start of the minimum 7-day discharge differs between the years. This attribute also shows a good pattern between blue and red point agglomerations. The starting day tends to be less variable for stations with their minimum 7-day discharge event early in the year. The highest variability can be observed for points that have their starting day in the late spring or early summer. The dependency is thus based on temporal but also altitudinal differences. We found no clear correlation between variance and catchment area (data not shown).

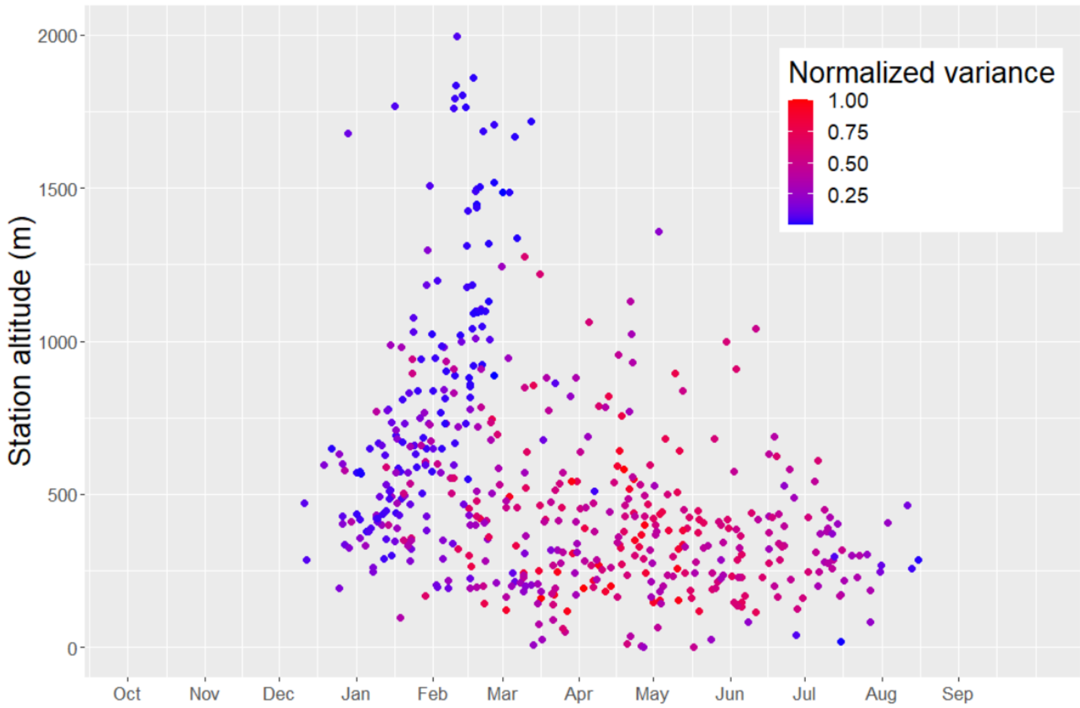


FIGURE 5.19: Mean start of a minimum 7-day discharge event by stations altitude for the reference period 1982-2011. The color scheme shows the normalized variance between single years. A high variance (represented by high values) indicating large differences of the start date between the years, stations with low variability are blue.

Chapter 6

Discussion

6.1 Discharge contribution

Our analyses have shown that each of the six clusters has individual runoff characteristics. The quantification of runoff contributions by delay classes has shown that the regions 'Jura', 'Plateau', and 'Southern Alps' are very similar. The relatively high contribution of short-delay is astonishing for the 'Jura'. A somewhat older study, which dealt with the runoff behavior of karst-dominated catchments in the Swiss Jura, showed that in these areas, the "fast-response" plays only a minor role for the runoff (around 20 %) (Siegenthaler et al. 1983). The relatively small contribution of short-delay response for the cluster 'Large catchment', on the other hand, seems plausible because stations with a large catchment tend to have longer mean distances between the measuring station and the catchment. However, this effect is also strongly related to precipitation intensity and soil saturation. McGlynn et al. have shown that delayed runoff responses occur primarily when precipitation intensity is low. They found significantly smaller differences with catchment size when precipitation was heavy, and soil was saturated (McGlynn et al. 2004). The increasing intermediate-delay contribution with increasing station elevation is consistent with the results of Stoelzle et al. 2020. In our results, however, it is particularly striking that the 'High-Alps' stations have relatively low baseline contributions (about 10 %). In contrast, the highest catchments of their study have contributions of slightly more than 20 %. However, these two figures are only comparable to a limited extent because our 'High-Alps' are about 500 m higher on average.

Analysis of runoff composition is an important measure to test the comparability of the two study regions. Significant differences in a corresponding cluster between the two study regions would mean that we could not directly compare them. However, as we have seen in the results, individual clusters of the two study regions hardly differ (differences of a few percent). The results show that the cluster classification worked quite well despite the different sizes of the two data sets. Based on this measure, there are no significant differences that need to be considered for further analysis.

6.2 Long-term discharge trend

To determine meaningful development trends, it is essential to have data series as long as possible. For the runoff development in the Alpine region, we could analyze time series of 90 years (for Switzerland) and 50 years (for the GAR), respectively. The results have shown that the change in annual runoff volume develops differently depending on the cluster, with a sharp north-south gradient. Thus, runoff volumes at stations north of the Alps have changed only slightly within the last 50 years, while runoff has decreased significantly on the southern side of the Alps. The Alps, which lies between these two regions, show apparent runoff increases, particularly for the 'High-Alps' stations. For stations of the 'Southern Alps' discharges have decreased significantly, particularly in spring and summer. Reasons for this may be the decrease of low-pressure weather types (Brugnara and Maugeri 2019), which is accompanied by fewer precipitation events, on the one hand, and the increase of evaporation rates due to higher temperatures, on the other hand. This so-called 'green water feedback' strongly affects runoff, especially in hot and dry summers. For example, a study analyzing the 2003 heatwave, Mastrotheodoros et al. 2020, found an amplification of the runoff deficit of over 30 % due to increased evaporation.
Of the six clusters, we found a significant runoff increase only for the 'High-Alps' stations. These results support the observed precipitation trends of this region (e.g., Auer et al. 2005; Brugnara and Maugeri 2019). However, the additional runoff volume exceeds the increase in precipitation (Birsan et al. 2005). According to our evaluations, the most significant increase in runoff occurred in spring and early summer. It corresponds to the season of snow and glacier melt. The study by Huss 2011 shows that glacier melt has a particular influence on the runoff volume in the summer months. Furthermore, they assume that summer runoff in high Alpine regions will continue to increase until about 2040 before it continuously decreases and falls below today's level until 2100.
Pellicciotti et al. 2010 could also show that the first runoff peak within the period 1974-2004 has shifted forward in time (due to increased precipitation in the form of rain instead of snow, causing the protective snowpack to melt earlier and leaving the underlying glacier ice longer exposed) which we could also detect in the rather significant runoff increase during the spring months and less significant increase during the

summer.
The large fluctuations in discharge volumes between the individual years are due, on the one hand, to natural variability, and on the other hand, to the prevailing weather conditions. The Northern Atlantic Oscillation (NAO) is a factor influencing precipitation and thus indirectly the runoff volume. The NAO index is based on the pressure differences between Iceland and the Iberian Peninsula. A pronounced difference (positive NAO index) leads to dry high-pressure weather in the Mediterranean region. In contrast, a negative NAO index results in weaker westerly winds, favoring cold air intrusions and a wetter climate in the southern Alpine region. A study of the western Italian Alps found correlations between NAO and winter precipitation. Depending on the region of the station, the influence of NAO was larger or smaller. While a positive phase of the NAO leads to dry-air convection with warmer temperatures and little snow, a negative NAO increases the advection of cold, moist air with larger snowfall amounts and longer persistence (Terzago et al. 2013). For stations all over Switzerland Birsan et al. 2005 could link high summer discharge volumes to the NAO index of the previous winter.
The comparison of annual discharge volumes between Switzerland and GAR stations for the period 1961-2011 shows only minor differences. They are particularly small for the clusters 'Jura' (Switzerland: 0.24 %/dec, GAR: 0.33 %/dec), 'Plateau' (Switzerland: 0.22 %/dec, GAR: 0.05 %/dec), 'High-Alps' (Switzerland: 3.78 %/dec, GAR: 3.13 %/dec), and 'Southern Alps' (Switzerland: -3.01 %/dec, GAR: -3.23 %/dec). For the other two cluster regions, the differences are also small, but there is a sign change. 'Large catchment' stations within Switzerland show slightly positive discharge changes (0.08 %/dec), those of the GAR are negative (-0.48 %/dec). The same is true for stations within 'Alps' (Switzerland: 0.07 %/dec, GAR: -0.89 %/dec). However, it should be noted here that the variations are not statistically significant.
In general, the trends between the two corresponding clusters of the two study regions are quite comparable. Due to the more extended time series of discharge data in Switzerland, we could also determine the trend for 90 years. For some clusters, the 90-year trend differs quite significantly from the 50-year trend. For example, the discharge in 'Jura' decreased over the 90 years, but an increasing trend can be observed if only the last 50 years are considered. The same is true for the stations of the clusters 'Large catchment', 'Plateau', and most clearly for 'Alps'. Considering the other two clusters ('High-Alps' and 'Southern Alps'), we see an intensification of the 90-year trend in the last 50 years. In summary, runoff in most regions has decreased over the long term (90 years). However, it has increased within the last 50 years, with this change being particularly pronounced at the high-elevated stations. In summary, a direct correlation between precipitation and runoff trends is evident and is especially

true for stations that have little or no glaciation (Farinotti et al. 2011). However, this is only one indicator for runoff determination. It has been shown that other factors such as snow and glacier melt in spring, but also evaporation in summer or long-term changes in prevailing weather patterns can alter runoff characteristics. We were also able to show that the selected period has a decisive influence on the results.

6.3 Pardé change

The analysis of the changes in the typical runoff regime characteristics has shown that the runoff variation throughout the year has decreased for most clusters. In other words, the difference between the month with the highest discharge and the month with the lowest discharge has become smaller. This can be seen particularly for Alpine catchments ('Alps' and 'High-Alps'). We could also observe a temporal shift of the regime curves for discharge stations north of the Alps. Thus, the average curve of the third period (1991-2010) is about half a month earlier than the regime curve for the period 1961-1980. Our results support the study results by Hänggi and Weingartner 2012, who had investigated the variations in runoff volumes associated with hydropower generation. However, considering only the regime curves, we cannot make any assumptions on changes in absolute water volumes. A decrease in the Pardé value for a given month implies only that the relative fraction of the annual runoff has become smaller. We have also shown that anthropogenic factors significantly influence the runoff behavior and could be the main reason for the more balanced regime curves, especially at the Alpine stations. In fact, and to a certain extent, dams can counteract climate change by storing specific water volume during months of high precipitation and runoff, which is used later during drier periods (Zampieri et al. 2016).
There are some differences between the two study regions, but most of them are relatively small. Due to the longer time series within Switzerland, the curve of the second period (1961-1980) corresponds to the first period within GAR. Most of the differences concern only single months of a cluster. For example, the May of the 'Large catchment' group is about 0.3 points higher within GAR than Switzerland. The largest differences can be seen in the cluster 'Southern Alps'. It is noticeable that the Swiss stations for the 1961-1980 time period do not have a pronounced second peak in late autumn, unlike the GAR stations for this period. Although there are some differences, it is difficult to distinguish between actual changes and changes caused by the small sample size. Apart from that, the runoff characteristics of the respective clusters are comparable. The temporal trends are also very similar across all clusters and through both study regions. Based on the Swiss stations, it can be seen that the 'flattening' of

the regime curves is not only detectable since the 1960s but also in the earlier discharge data.

6.4 Extreme year analysis

By evaluating the extreme year analysis, we determined individual years with particularly low runoff. We found that there is often a spatial correlation of individual years, similar to the process of clustering. We also often observed a good fit between boundaries of clusters and those of extreme years. For example, at 60% of all stations of the 'Large catchment' (Switzerland), the year 2011 had the lowest discharge. We also see a similar situation for the corresponding cluster within the GAR, whereas many as 47% of the stations have a record year. There are different explanations for this. For example, the similar behavior between the two study regions is not so much explained by meteorological characteristics but rather the result of cluster assignment, leading to similar spatial categorizations. Thus, these similarities are more indirectly due to hydrologic characteristics rather than the direct result of spatial conditions.
In contrast, determining the correlation between an extreme year and the clusters is much more complex. The difficulty is accurately attributing a pattern to either the characteristics of the catchment or the prevailing weather. Perfect differentiation does not appear to be practical or even possible. On the one hand, cluster categorization is indirectly based on spatial conditions since the runoff regime is directly influenced by factors such as elevation or climatic zone; on the other hand, an extreme year occurs only when the specific meteorological conditions are present. Extreme events, which affect the runoff volume of a catchment for a longer period, are determined mainly by long-lasting weather conditions. Resulting heat waves or droughts often affect a large area (Quesada et al. 2014). Therefore, the question is not which weather situation led to which effects in a particular area, but to what extent a prevailing weather situation affects the individual regions. For example, during the European-wide heatwave in the summer of 2003, temperatures also rose sharply at higher elevation stations in the Alpine region (Rebetez 2004), resulting in comparable weather situations over the entire study area. However, the runoff data showed different effects depending on the region (and thus on the cluster). While high Alpine stations recorded runoff increases, lower fed rivers carried very low levels.

6.5 Minimum 7-day discharge

The analysis of return periods is a measure to study the frequency of a specific event (in this case, the minimum 7-day runoff) and depends only indirectly on the catchment regime. Catchments with large runoff variations within a year react differently to a dry period than those with constant runoff. The greater the variation, the more extreme a low flow event must be to result in a high return period. If we have a runoff deficit within a balanced catchment regime, we are more likely to get higher return periods. We used two different approaches to evaluate the return periods. On the one hand, we quantified the events using simulations, and, on the other hand, we compared and ranked individual years by calculating the rank plots.
Our results have shown that we can divide our stations into three regions based on their characteristics. On the one hand, the group of stations north of the Alps ('Jura', 'Large catchment', and 'Plateau') differs from those on the southern side of the Alps and even more clearly from the Alpine ones ('Alps' and 'High-Alps'). The differences are shown by a different pattern of years (months) with particularly high return periods and by general differences. For example, the Alpine stations tend to have significantly lower median return periods than stations north and south of them. One possible explanation for this is the composition of a region's runoff and the timing of low flows. The Alpine stations typically have relatively low discharges in the winter half since most of the precipitation falls in form of snow and is not directly added to the runoff. In winter with low precipitation, this deficit has less impact on the runoff than at stations of lower elevations. The situation is different in the summer months. Typically, the largest part of the total annual runoff at Alpine stations is discharged during this season. If there is an extremely dry (and hot) summer, the runoff volume of all stations is reduced. At Alpine stations, which have snow and glaciers in their catchment area, the lack of precipitation can be (partially) compensated by additional meltwater. Therefore, the runoff of Alpine stations is not as affected by precipitation as the rest of the catchments.
The cross-comparison between the clusters of Switzerland and those of the GAR also shows partly significant differences within a group of clusters. It is noticeable that the return periods within the Swiss clusters tend to be larger. This is particularly pronounced for the two clusters 'Jura' and 'Southern Alps'. A possible explanation for the significant differences, at least for the 'Southern Alps', could be the relatively small number of stations combined with their spatial distribution. Within Switzerland, we have only eight stations, all located in a relatively small area in Ticino. If we look at that cluster on a European scale, we see in addition to the "Ticino block" a cluster at the Italian-Slovenian border, about 350 km east of it. This considerable distance may

pose a problem for comparability, especially since the number of stations is relatively low, and thus the two "blocks" could differ in catchment characteristics.
The evaluation of the extreme events has shown that, in addition to the cluster affiliation, the geographical spatiality can also have a massive influence on the runoff of individual years. We can therefore assume that despite the same cluster affiliation, certain variations exist between the two "blocks" of 'Southern Alps' stations, and therefore a mixed evaluation (GAR) provides different results than if only one of the two "blocks" (Switzerland) is used.

Chapter 7

Conclusion

Our analysis aimed to characterize runoff behavior in the European Alpine region and to identify changes over the last decades. We wanted not only to describe general changes but also to highlight spatial differences. For this purpose, we assigned our stations to different cluster groups based on their long-term regime curves and using the k-Means clustering algorithm. We could essentially identify six different types, which differ not only based on discharge characteristics but also spatially (both within Switzerland and for the GAR). In the 'Jura' region, runoff is characterized by particularly low summer runoff and somewhat higher winter runoff. The situation is similar in the 'Plateau' region, where the runoff variability within a year is rather low. The stations representing a 'Large catchment' show a slightly higher runoff contribution in summer and a lower winter runoff than the 'Plateau' stations mentioned above. Different runoff behavior can be seen at stations in the Alps. Both 'Alps' and 'High-Alps' have peak discharge in the summer months, and Pardé coefficients >3 are not uncommon. In contrast, runoff is very low in the winter months, especially in the 'High-Alps'. The sixth cluster groups stations south of the Alps. Compared to all other clusters, this is the only one with two typical runoff peaks per year. On the one hand, in spring (May) and on the other hand in late autumn (October). In between, we have relatively low runoff values. Another variable for describing cluster-specific characteristics is the partitioning of runoff by delay classes. In this context, stations south of the Alps behave very similarly to stations in the Jura region or the Central Plateau and react faster to precipitation events (larger short-delay contribution) than stations of high-elevation catchments, which show a somewhat delayed runoff (large intermediate-delay contribution) and low contributions of 'baseflow'.

Another goal of our study was to quantify the temporal changes in runoff volumes. We found that for this purpose, the Alpine region can be divided into three regions. North of the Alps ('Jura', 'Large catchment', 'Plateau', and 'Alps'), the changes in annual runoff volumes over the last 50 years are not very large, although a slight tendency of a decrease can be observed. The stations in the 'High-Alps', on the other hand, show a significant increase in total annual runoff, while on the south side of the Alps, runoff has tended to decrease. We also found that these changes are due to different seasons depending on the region. While winter runoff increased north of the Alps, summer runoff, on the other hand, decreased to the same extent, resulting in a balanced annual balance. The winter runoff increase can also be observed for stations in the 'High-Alps'. However, contrary to the stations north of the Alps, the summer runoff also increased, both contributing to a positive runoff balance. On the southern side of the Alps, the significant decreases in summer runoff are particularly decisive, which are not fully compensated by the slight winter increases. Furthermore, we could show that these trends have strengthened recently (50-year trend compared to 90-year trend). These trends also affect the regime properties of a cluster in the long term. Our analyses on changes in Pardé coefficients reflect this. On the one hand, we can observe decreasing differences between the month with the highest and the one with the lowest runoff for most stations. On the other hand, we see the temporal forward shift of the Pardé curves for stations north of the Alps. Reasons for these changes are manifold and vary depending on the region. There are climatological changes with higher temperatures and altered precipitation patterns (form, amount, and seasonal timing) which have an impact. However, direct human influences (for example, due to the construction of hydropower plants or dams) can have a decisive impact on a region's runoff characteristics.

With the third research question, we addressed the low flows. It has been shown that the differences are mainly divided among three major regions. 'Jura', 'Large catchment' and 'Plateau' have both a very similar pattern in terms of minimum 7-day discharge of a single year and seasonality. The return periods of the minimum 7-day discharges are generally somewhat higher than those of the Alpine catchments. We also see some differences in extreme years; for example, the summer of 2003 was particularly dry. Low discharges were observed in much of the lower elevation stations, while high Alpine stations tended to have above-average discharges. In addition to the northern and Alpine stations, we have the southern side of the Alps as a third region. Although these stations tend to be similar to those north of the Alps, there are specific differences, representing the year 2003, which, in contrast to the other regions, recorded extremely low discharges already in spring.

In addition, we performed further evaluations to test the comparability between the two study regions. On the one hand, this was the extreme year analysis, in which the most extreme year of each station was determined independently of the cluster and then compared with the cluster distributions. We found correlations between individual years and clusters for both study regions equally. On the other hand, we compared the median return period of minimum 7-day discharges of individual clusters and found very similar results, especially between the Alpine stations of both study regions. Stations south of the Alps are less comparable, which may be due to the low station number, but also to the very specific local characteristics.

Chapter 8

Outlook

Finally, we would like to explain some aspects that could have been carried out in addition to the analyses discussed, but which were not possible due to time, available data, or the scope of the work.

Direct adaptations to our analyses include the homogenization of the data sets used (increasing the compatibility of the individual data sets), the evaluation of additional hydrological variables (e.g., minimum 30-day discharge), or an alternative classification methodology for all stations (e.g., based on elevation, catchment size, exposure, or climate zones). The studies could additionally be complemented by more runoff data or more extended time series. Especially in the Italian Alpine region, the station density is relatively poor, so certain regions are not covered. Although we have made some efforts to obtain additional data, this has mostly proved difficult. The chances of success would possibly be higher if data acquisition were made via joint research programs (such as ADO) and central databases. In addition to a larger spatial coverage, the temporal analysis period could also be extended. More extended time series would not only provide a basis for trends over a longer period. However, they could also be used to compare different periods, so that observed relationships (e.g., seasonal runoff development with glacier melting behavior) could be described in more detail. Such long-term evaluations could also be used to convert observed changes in hydrological variables to changes in climate. This understanding would have been crucial if one had wanted to simulate future runoff developments under different climate scenarios. Furthermore, it would have been possible to compare catchments with similar runoff characteristics but different regions. CAMELS data sets (Catchment Attributes and Meteorology for Large-sample Studies) could provide a possible data basis for this purpose.

Appendix A

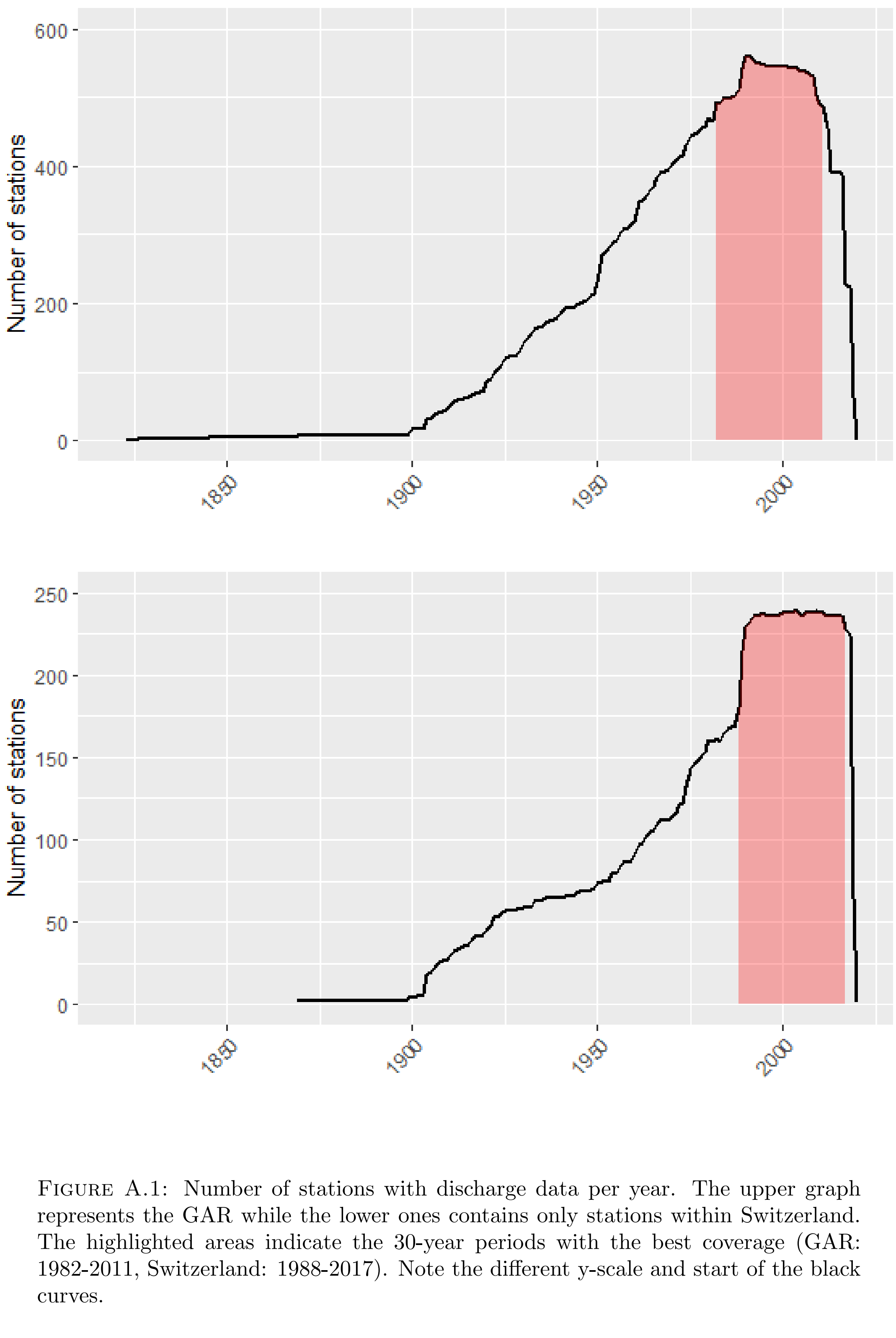


FIGURE A.1: Number of stations with discharge data per year. The upper graph represents the GAR while the lower ones contains only stations within Switzerland. The highlighted areas indicate the 30-year periods with the best coverage (GAR: 1982-2011, Switzerland: 1988-2017). Note the different y-scale and start of the black curves.

TABLE A.1: Structural changes affecting the discharge behavior of a station. KW = Power station (Kraftwerk), LKW = River power plant (Laufkraftwerk).

Station	Year	Influence
Andermatt	1945	Drainage to Lago di Lucendro
	1960	Drainage to Göscheneralpsee
Brienzwiler	1932	KW Handeck 1
		Grimselsee
	1943	KW Innertkirchen 1
	1950	KW Handeck 2
		Räterichsbodensee
	1953	Oberaarsee
	1954	KW Grimsel 2
	1961	KW Fuhren
	1967	KW Innertkirchen 2
	1974	KW Grimsel 1
	1976	KW Handeck 3
Domat-Ems	1957	Zervreilasee
	1961	Lago di Lei
Ilanz	1962	Lai da Nalps
	1966	Lai da Curnera
	1968	Lai da Sontga Maria
Le Chable, Villette	1957	Lac de Mauvoisin
	1964	KW Chanrion
Luzern, Grossmattbr.	1998	LKW Mühlenplatz
Martina	1968	Lago di Livigno
		Lai dad Ova Spin
	1993	Pradella
Piotta	1944	Lago di Lucendro
	1947	Lago della Sella
	1968	KW Stalvedro
Seedorf	1945	Lago di Lucendro
	1960	Göscheneralpsee
Sion	1957	Lac des Dix
		Lac de Tseuzier
	1958	Lac de Moiry
	1967	Lac de Mattmark
St.Moritzerbad	1945	KW Islas
Visp	1960	KW Saas-Fee
	1961	Stafel
	1965	Z'mutt
		Zermeiggern
		Stalden
	1967	Mattmark

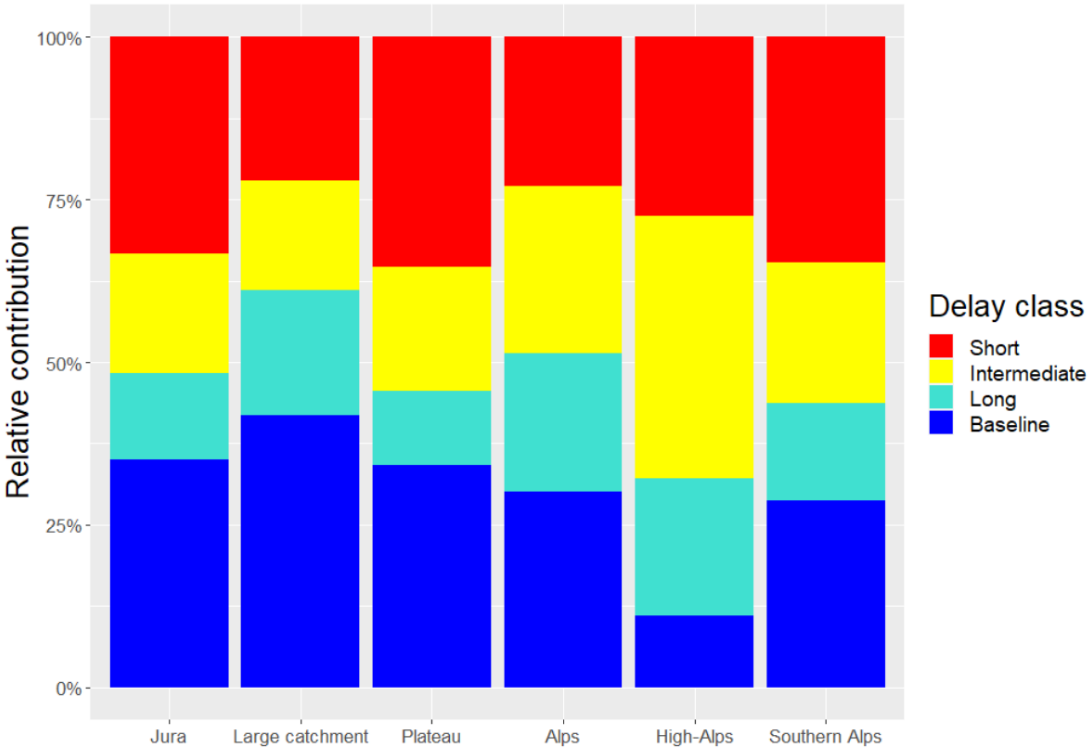
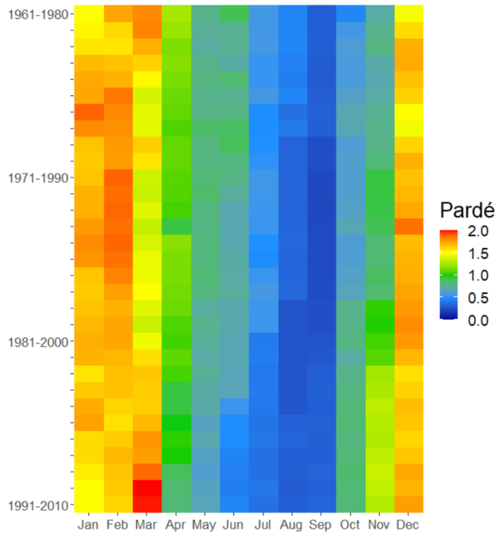
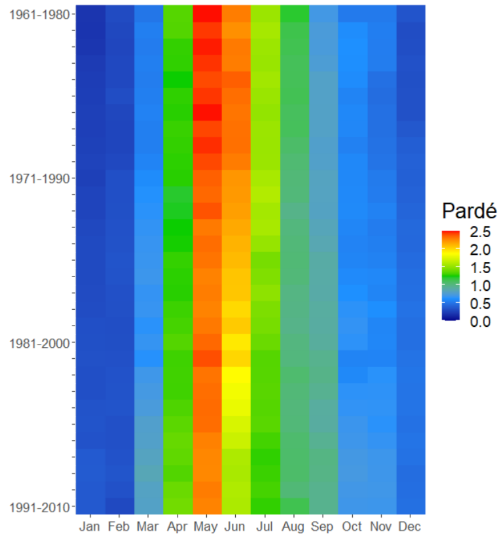


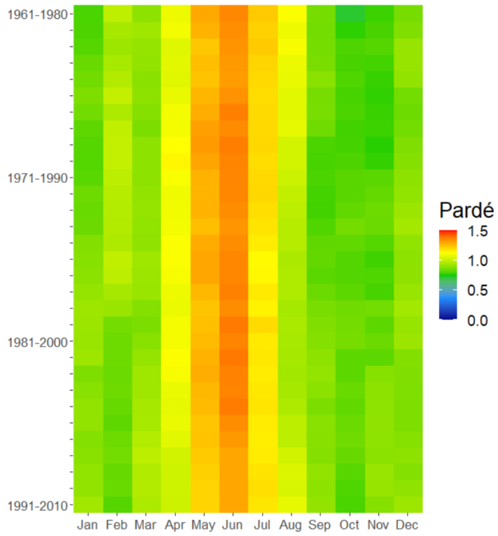
FIGURE A.2: Relative contribution of the four delay classes by cluster. The values are calculated using discharge data for the period 1982-2011.



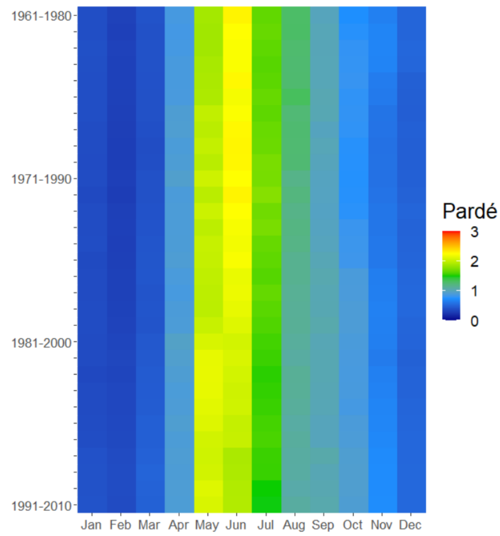
(A) Jura - Schwabsberg (DE)



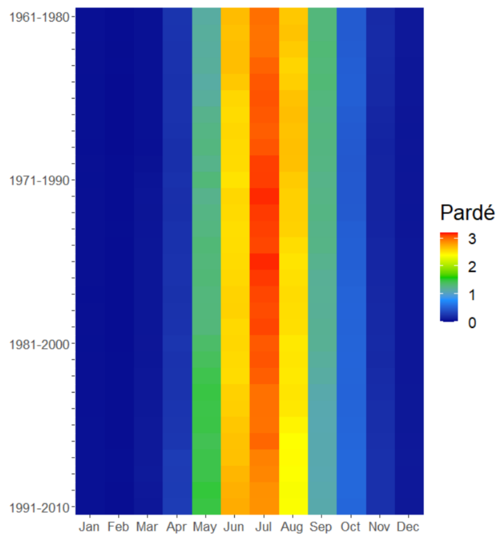
(B) Large catchment - Au (CH)



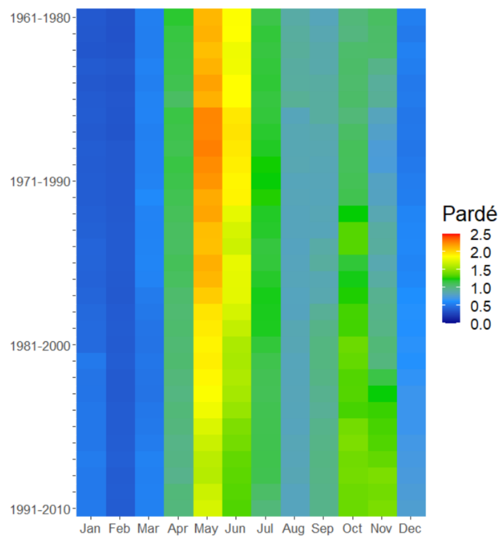
(C) Plateau - Brugg (CH)



(D) Alps - Mauterndorf (AT)



(E) High-Alps - Matreier (AT)



(F) Southern Alps - Rattendorf (AT)

FIGURE A.3: Time variation of the Pardé coefficient. Note the different scales.

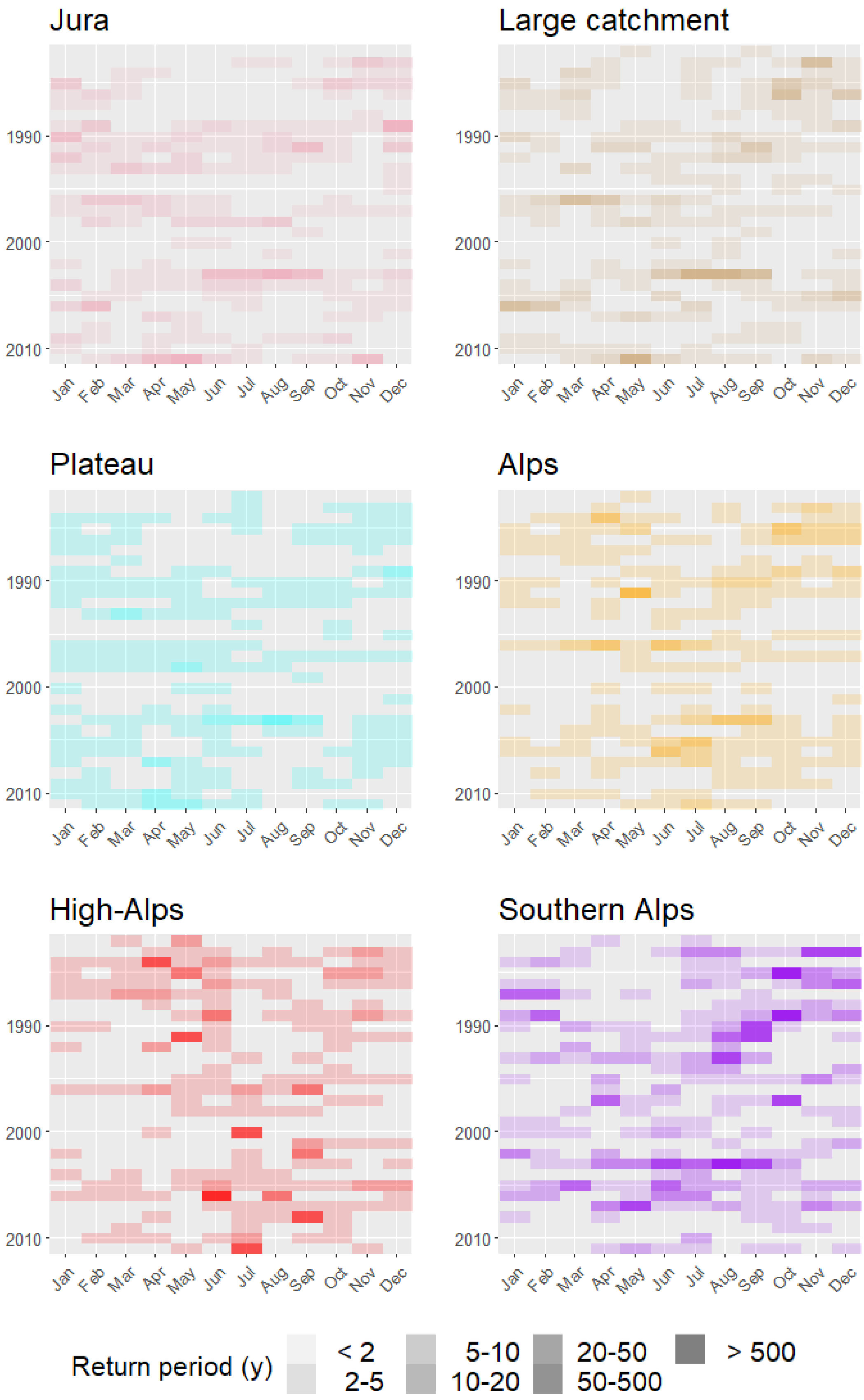


FIGURE A.4: Median return period of the lowest 7-day discharge of all catchments within a cluster.

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Declaration of Authorship

Personal declaration: I hereby declare that the submitted Thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the Thesis.

Zurich, 07/31/2021

Michael Eichmann