



**Flood-triggering
precipitation in
Switzerland**

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Flood triggering in Switzerland: the role of daily to monthly preceding precipitation

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Abstract

Determining the role of different precipitation periods for peak discharge generation is crucial for both projecting future changes in flood probability and for short- and medium-range flood forecasting. We analyze catchment-averaged daily precipitation time series prior to annual peak discharge events (floods) in Switzerland. The high amount of floods considered – more than 4000 events from 101 catchments have been analyzed – allows to derive significant information about the role of antecedent precipitation for peak discharge generation. Based on the analysis of precipitation times series, we propose a new separation of flood-related precipitation periods: (i) the period 0 to 1 day before flood days, when the maximum flood-triggering precipitation rates are generally observed, (ii) the period 2 to 3 days before flood days, when longer-lasting synoptic situations generate “significantly higher than normal” precipitation amounts, and (iii) the period from 4 days to one month before flood days when previous wet episodes may have already preconditioned the catchment. The novelty of this study lies in the separation of antecedent precipitation into the precursor antecedent precipitation (4 days before floods or earlier, called PRE-AP) and the short range precipitation (0 to 3 days before floods, a period when precipitation is often driven by one persistent weather situation like e.g. a stationary low-pressure system). Because we consider a high number of events and because we work with daily precipitation values, we do not separate the “antecedent” and “peak-triggering” precipitation. The whole precipitation recorded during the flood day is included in the short-range antecedent precipitation.

The precipitation accumulating 0 to 3 days before an event is the most relevant for floods in Switzerland. PRE-AP precipitation has only a weak and region-specific influence on flood probability. Floods were significantly more frequent after wet PRE-AP periods only in the Jura Mountains, in the western and eastern Swiss plateau, and at the exit of large lakes. As a general rule, wet PRE-AP periods enhance the flood probability in catchments with gentle topography, high infiltration rates, and large storage capacity (karstic cavities, deep soils, large reservoirs). In contrast, floods were

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significantly less frequent after wet PRE-AP periods in glacial catchments because of reduced melt.

For the majority of catchments however, no significant correlation between precipitation amounts and flood occurrences is found when the last three days before floods are omitted in the precipitation amounts. Moreover, the PRE-AP was not higher for extreme floods than for annual floods with a high frequency and was very close to climatology for all floods. The weak influence of PRE-AP is a clear indicator of a short discharge memory of Prealpine, Alpine and Southalpine Swiss catchments. Our study nevertheless poses the question whether the impact of long-term precursory precipitation for floods in such catchments is not overestimated in the general perception. We conclude that the consideration of a 3–4 days precipitation period should be sufficient to represent (understand, reconstruct, model, project) Swiss Alpine floods.

1 Introduction

River flooding is one of the most devastating and costly natural hazards in Switzerland (Hilker et al., 2009) and worldwide (Munich Re, 2014). Damaging flood events in the Alps are often caused by high precipitation events that last for several days (e.g. Massacand et al., 1998; Hohenegger et al., 2008; Stucki et al., 2012). However, river discharge during floods can also be influenced by both the spatial and temporal characteristics of the precipitation event and by the state of the catchment before the precipitation event, i.e. the antecedent conditions. One of the most important antecedent factors is the total water storage in the form of snow, soil water, ground water and surface water. In particular, the importance of antecedent precipitation for floods has long been emphasized (especially for large catchments). For example, effort is invested in designing continuous hydrological simulations which allow to account for year-long antecedent precipitation time series when assessing discharge extremes (see e.g. Wit and Buishand, 2007, for the Rhine and Meuse basins).

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For several recent catastrophic flood events antecedent water storage was important. For example, Reager et al. (2014) point to the importance of a positive water storage anomaly for the 2011 Missouri floods. The floods in June 2013 in Central Europe were preceded by above-average precipitation during the second half of May that influenced the flood discharge by presaturating the soils (Grams et al., 2014). Schröter et al. (2015) further show that this exceptional flood event resulted from the combination of non extraordinary precipitation with extremely high initial wetness. For the floods of 2002 also in Central Europe, Ulbrich et al. (2003) describe several intense rainfall episodes in the first half of August that finally lead to the extreme discharges. In southern Switzerland, severe flooding of the Lago Maggiore in September 1993 was preceded by a series of high precipitation events in the watershed (Barton et al., 2014). Antecedent conditions might even be relevant for the development of flash floods: Marchi et al. (2010) found that the runoff coefficient, i.e. the fraction of the total rainfall that is routed into runoff, of 58 flash floods in Europe was statistically higher for wetter antecedent precipitation. They however also found that, although flash floods are more frequent after wet antecedent conditions in Central Europe, they primarily occur following dry conditions in the Mediterranean region and show no dependence on the antecedent conditions in the Alpine-Mediterranean region. For large Swiss lakes and streams, Stucki et al. (2012) underline the importance of high soil saturation due to excessive water supply by enhanced melt and precipitation over several months for the generation of historical floods.

However, damages in Switzerland often occur when small rivers overflow or when surface runoff occurs outside of river beds (Bezzola and Hegg, 2007). The devastating event of 1993 is a memorable example of how a local river can generate high damages (Hilker et al., 2009). Local floods in Switzerland result from a large variety of hydrological processes (depending on the region, floods may be driven by short but intense showers, continuous rainfall, rain on snow, or snow and/or glacier melt; see Merz and Blöschl, 2003; Helbling et al., 2006; Diezig and Weingartner, 2007). Defining the influence of antecedent precipitation for this large variety of flood types is a complex

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task. A modeling study by Paschalis et al. (2014) showed that soil saturation can play a paramount role in mediating the discharge response of a small Prealpine catchment. The initial conditions also significantly affect flash flood forecasting in the Southern Swiss Alps (Liechti et al., 2013). However, Norbiato et al. (2009) found that the impact of initial moisture conditions on the runoff coefficient during floods is important only for catchments with intermediate subsurface water storage capacity; i.e. the role of initial moisture conditions is negligible for catchments with either very large or very small storage capacity. Also, reports from Ranzi et al. (2007) on observed floods in mesoscale Alpine catchments with relatively shallow and permeable soil layers conclude that "... values of antecedent precipitation do not dramatically affect the resulting runoff coefficient, at least during major floods. This indicates a smaller sensitivity to initial soil moisture conditions than generally assumed ...".

Apart from case studies and modeling studies of single catchments, the relationship between precipitation and flooding has never been investigated in a comprehensive and systematic manner in Switzerland.

A better understanding and quantification of the role played by antecedent precipitation in the development of floods is crucial for flood hazard management for two reasons:

- i. Because future flood frequency changes might depend on the role of antecedent precipitation. Future changes in precipitation for Switzerland are still uncertain (CH2011, 2011) but general tendencies can be derived from the projections. In summer, the most important season for Alpine floods, a clear decrease in mean precipitation (due to drier soils) is expected to be accompanied by a weak increase in extreme daily precipitation (due to warmer air, see Rajczak et al., 2013). Thus, depending on whether short-term or long-term precipitation is more important for floods, flood frequency might increase or decrease in the future.
- ii. Due to the relatively long residence time of water in catchments with significant moisture storage capacity, information regarding the current moisture state can

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help to improve medium-range flood forecasting. Identifying catchments where the amount of antecedent precipitation is particularly determinant for floods may help to determine critical regions where an efficient use of that information is primordial for flood forecasting systems. For example, it is now possible to derive water storage information from satellite data, and Reager et al. (2014) demonstrate a great potential for warning systems at weekly to seasonal lead times.

Here, we do not aim to quantify the role of antecedent precipitation by calculating runoff coefficients like in previous studies. Instead, we make use of two large networks of rain gauges and river discharge stations to derive robust statistics from a large number of events. The underlying hypothesis is that if a period of antecedent precipitation influences the amplitude of peak discharges, floods should be significantly more frequent after wet conditions during that period provided that a sufficient sample of events is investigated. The following questions are addressed in particular for different precipitation periods before floods (e.g. 0–1, 3–14 days before floods):

- i. In the past 50 years, have floods in Switzerland been significantly more (or less) frequent after wet conditions during that period?
- ii. If they were more frequent, can we define catchment properties that determine whether and how strongly that period influences flood probability?
- iii. Did extreme floods follow wetter antecedent conditions than smaller discharge peaks?
- iv. Which precipitation accumulation period is most closely related to flood occurrence?
- v. How many days of antecedent precipitation are relevant for floods?

We aim to explicitly separate short-range and long-range antecedent precipitation and thus discuss the temporal separation of different precipitation accumulation periods. The analysis comprises thousands of annual maximum discharge events in a large

sample of catchments representative of the various hydrological regions of Switzerland. This analysis is unique for Switzerland in regard to the amount of floods considered and, to our knowledge, also unprecedented worldwide.

2 Data

The events analyzed in this study are 4257 annual maximum instantaneous discharge measurements (called floods hereafter). They were recorded at 101 stations during the period 1961 to 2011. The data is provided by the Swiss Federal Office of the Environment (FOEN)¹. The stations measure water level from which a discharge value is obtained through a rating curve that is based on regular discharge measurements. In the case of extreme floods, the discharge values have been manually checked and, if required, have been corrected by hydraulic modeling and expert judgment. All annual maximum discharge events are denoted HQ hereafter. HQs exceeding the 5 and the 20 year floods will be denoted HQ5 and HQ20, respectively. Note that HQs of estimated return periods of more than 100 years have been recorded in the last decades. Here those floods are simply included in the HQ20 sample (return period larger than 20 years). The distinction of higher return periods than 20 years is avoided in order to maintain a large sample size.

We use gridded daily precipitation accumulations constructed from interpolation of a dense network of rain gauges (see Frei and Schär, 1998). The daily sums (from 06:00 to 06:00 UTC) are available on a 0.02 by 0.02° grid covering the Swiss territory for the period 1961–2011 (hereafter RhiresD, see MeteoSwiss, 2011). The number of gauges varies from approximately 400 to 500 throughout this time period. The effective resolution of the dataset, given by the typical inter-station distance, is approximately 15–20 km. Some of the smallest catchments investigated here may not contain any

¹<http://www.bafu.admin.ch/index.html?lang=en>

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catchment. Some of this information is available within the Hydrological Atlas of Switzerland (see table of plate 5.6 from Aschwanden and Spreafico, 1995). Only Micro and Meso catchments with no or low human influence were selected. Some human influence was tolerated for Macro catchments. Discharge is regulated at the exits of the majority of large Swiss lakes and the lake exit stations are analyzed separately (hereafter “Lakes Exits”). Karstic catchments with very complex underground flow were removed based on expert knowledge.

The Swiss landscape contains distinct geographical and hydrological regions: the Alps (Prealps, High Alps, Southern Alps), the Swiss Plateau and the Jura Mountains. Each region shows specific hydro-meteorological properties. In order to account for this diversity, a typical hydrological regime has been attributed to each Micro and Meso catchment (see Fig. 1). This classification of hydrological regimes follows Aschwanden and Weingartner (1985); see also Weingartner and Aschwanden (1992). A first set of separation criteria is the mean elevation and the glacier coverage. These properties allow us to distinguish between Glacial (mean altitude > 1900 m and glacial coverage > 6 % or mean altitude > 2300 m and glacial coverage > 1 %), Nival (mean altitude > 1200 m) and Pluvial regimes. Then, all catchments from the southern side of the Alps were joined in the Meridional group. The specific precipitation regime (Schmidli and Frei, 2005) and flood seasonality (Köplin et al., 2014) of this group, as well as the specific geology (crystalline, poor infiltration rates, steep slopes, and weak soils) motivated this choice. Similarly, the catchments in the Jura Mountains were joined in the Jurassien regime type because of their shared specific morphology and geology (high plateaus, gentle slopes, high infiltration rates and important network of underground streams due to the calcareous and karstic bedrock).

From Glacial to Nival to Pluvial, the flood seasonality decreases but a maximum flood frequency in summer is maintained. Meridional catchments are characterized by a maximum flood frequency in fall and summer and Jurassien catchments by winter floods with rain on snow as a major flood process (see e.g. Piock-Ellena et al., 2000; Köplin et al., 2014).

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In summary, the different catchment subsamples are: Micro (52 catchments), Meso (35 catchments), Macro (8 catchments), Glacial (19 catchments), Nival (17 catchments), Pluvial (31 catchments), Meridional (8 catchments), Jurassien (12 catchments.) and Lakes Exits (7 catchments). See Table 3 for a brief description of each catchment.

3.2 Derivation of precipitation time series for each catchment

We identified catchment area boundaries for each discharge station by applying a purely topography-based approach to a digital elevation model (DEM) with a 10 m resolution. For most of the Swiss territory, the effective drainage areas of the stations can be expected to be reasonably close to the catchments derived from the DEM. Critical regions are the highly karstic areas in the Jura Mountains and some areas of the Prealps, where the hydrological and topographical catchments tend to be significantly different because of the complex underground flow (see e.g. Malard and Jeannin, 2013). The most critical catchments were not considered for the analysis.

Area-averaged precipitation time series were obtained by combining the gridded precipitation data with the topographical catchment areas.

3.3 Definition of precipitation periods

A set of precipitation accumulation periods (PAPs) was defined (summarized in Table 1). Most PAPs represent a precipitation sum over a particular period before the flood day and two more PAPs are based on the concept of antecedent precipitation indices (API). A detailed description of the PAPs and the motivation for choosing them is given in Sect. 4.1. For example, PAP D4-14 is the precipitation sum that occurred within the period from 14 to 4 days prior to the flood day. PAPs are calculated for each day of the catchment-averaged precipitation time series (not only for flood days). The precipitation sums corresponding to flood days are then compared to the climatological distribution of all precipitation sums. The climatological distribution is defined as

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a ± 45 days range for each day of the calendar year. For example, let us assume that a flood occurred on the 1 June 2000. The D4-14 of that day is compared to all 11 day precipitation accumulations between 17 April and 16 July from 1979 to 2011 and the respective percentile of D4-14 is calculated. For each flood event we can thus determine the percentile value for each PAP. A range of ± 45 days is an optimal compromise between minimizing the effects of precipitation seasonality and maximizing the climatological sample size (91 days per year times 20–50 years means that each value is compared to 1820–4550 other values).

Beside the simple precipitation sums, more complex indices for antecedent precipitation, i.e. APIs are used. APIs have been commonly used in hydrology for decades (see e.g. Kohler and Linsley Ray, 1951; Pui et al., 2011). We follow the method of Baillifard et al. (2003):

$$API_i = P_i + KP_{i-1} + K^2P_{i-2} + \dots + K^nP_{i-n} \quad (1)$$

where P is the daily precipitation sum, i is the day for which API is calculated and K is the decay factor. Here, a constant K value of 0.8 is used for all catchments. The decay factor K is a proxy for diverse water fluxes that lead to a reduction of the water stored in a catchment. In this study, a decay rate of 20 % per day, i.e. $K = 0.8$, is chosen and reflects roughly typical conditions in Switzerland (Baillifard et al., 2003). Results are insensitive to a tested range of K between 0.7 and 0.9. We use the indices API2 and API4 that include all days of the time series up to 2 and 4 days before the flood day (hereafter also called PAPs).

3.4 Logistic regression

The underlying hypothesis of this study is that, if a PAP is important for flood generation, a significant signal can be detected using the logistic regression. A lack of significance on the other hand, implies either that the PAP has no influence on flood probability or that this influence is too weak to be significant during the investigated period.

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In Sect. 4.4 we assess the importance of the different PAPs for peak discharge generation at each catchment. A test is performed for each catchment and each PAP separately using a logistic regression model.

Binary daily time series of floods $y(t)$ and precipitation $PAP_T(t)$ are calculated. The time series contain approximately 7000 to 18 000 days t . For days when floods were recorded $y(t) = 1$ and $y(t) = 0$ for all other days. For days when the PAP exceeded a given percentile threshold $TPAP_T(t) = 1$ and $PAP_T(t) = 0$ for all other days. The model is then fitted as follows:

$$\text{logit}(p(t)) = \beta_0 + \beta_1 \text{PAP}_T(t) \quad (2)$$

where $\text{logit}(x) = \log(x/(1-x))$, and $p(t)$ is the probability of observing a flood at day t given the predictor, i.e. $p(t) := P(y(t) = 1 | \text{PAP}_T(t))$.

We are particularly interested in the value of β_1 . The odds ratio ($O = \exp(\beta_1)$) is a measure for the increase (or decrease if O is below 1) of the odds, $p/(1-p)$, of a flood occurring when the PAP exceeds percentile T . Here, p is by definition small (we look at yearly discharge maxima and even rarer events) and we can therefore set $p/(1-p) \approx p$ and the odds ratio can thus be understood as a multiplicative factor for the flood probability p . Statistical testing can assess the significance of the predictor PAP_T . A significant p value implies that “the exceedance of a given precipitation threshold significantly changes the flood probability”.

Note that working with binary predictors is not mandatory in logistic regression. Here this choice offers the advantage of avoiding the assumption that $\text{logit}(p)$ is proportional to the percentile of the precipitation period; an assumption for which no particular argument could be found. A drawback is however that the regression can only be performed with predefined thresholds. Here, the logistic regressions are tested for 5 different thresholds (P50, P75, P90, P95, P99) and the p value of the most significant test is selected (the corresponding thresholds and odd ratios are not discussed).

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4 Results

Hereafter, we will use percentiles to describe precipitation intensities. To simplify the language, we define a set of expressions (see Table 2).

4.1 Defining different precipitation periods preceding Swiss floods

5 The first challenge is to distinguish between event and pre-event precipitation. Flood triggering precipitation can be in the form of synoptically driven precipitation (periods lasting between a few hours to several days when the synoptic situation is particularly conducive to repeated precipitation events) and/or localized and short lived high precipitation events (typically convective). Ideally, a flood-by-flood analysis using a hydro-
10 logical model should be performed to determine the exact time lag between the most intense precipitation rate and the discharge peak, as well as to merge all precipitation events that would be attributed to a particular synoptic situation, such as the passage of a cyclone. However, a case-by-case analysis is beyond the scope of this study first because the daily resolution of the data does not allow for an evaluation of precipitation
15 rates on sub daily timescales and second because of the very large number of events considered. Instead, we search for simple indices, i.e. PAPs that will (on average) best represent the precipitation associated with all floods in Swiss rivers.

In order to determine the optimal separation of precipitation periods for the sample of events considered, the precipitation distribution is first investigated day by day. Figure 2a shows the distributions of daily precipitation sums for every day prior to and
20 after all floods. For example, the boxplot at $x = -10$ represents the distribution of precipitation sums recorded 10 days before all floods (4257 values of daily precipitation recorded 10 days prior to the 4257 flood days). Moderate to intense precipitation is most often recorded one day before floods when the 80th local seasonal percentile is exceeded in 75 % of the cases and the median precipitation sum corresponds to the
25 98th climatological percentile. During flood days, the median precipitation only amounts to percentile 93. The days -2 and -3 also show high precipitation sums with medians

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amounting to climatological percentiles 75 and 60, respectively. From day -4 backwards, the precipitation distribution is very close to climatology, although it tends to be slightly enhanced up to 10 to 15 days before floods. Similar results are observed when subsamples of catchments are analyzed (Fig. 2b–d). The maximum median daily precipitation is recorded 0–1 days before HQ days at Micro catchments and 1–2 days before HQ days at Lakes Exits. A clearly enhanced median precipitation prior to 4 days before HQ days is only found at Lakes Exits.

Daily precipitation sums correspond to the 06:00 to 06:00 UTC accumulations and are therefore shifted by 5 h compared to discharge peaks recorded on calendar days. This partly explains the one-day shift between maximum precipitation and HQ occurrence, especially for the floods in Micro catchments. The response time of catchments, i.e. the time between precipitation and registration of the related runoff at the gauge, plays a role as well. We therefore group the flood days and the preceding days together (hereafter the PAP called D0-1; see also Table 1). This is the time range when intense precipitation rates are most likely. As shown in Fig. 2b and c, this assumption is valid for Micro and Macro catchments whereas for Lakes Exits the most intense precipitation occurs 2 days before floods (because of longer response times due to lake retention). Intense precipitation events responsible for flood peaks might be very short (hours or minutes in the case of flash floods) but the daily resolution of the data and the shift between precipitation and floods does not allow for a further separation of the time windows.

Precipitation 2 to 3 days before floods is also greater than climatology in all catchments and, interestingly, precipitation remains also greater than climatology 2 days after floods in Fig. 2a. An explanation for this phenomenon can be found in Fig. 2e, which shows the results of an analysis similar to the one of Fig. 2a but applied to maximum precipitation days instead of flood days. In Fig. 2e, the precipitation distribution is similarly enhanced ± 2 days around high precipitation events like it is enhanced around flood events. The typical time scale of precipitating weather systems over Europe leads to some persistence of the daily weather situations so that daily precipitation time series

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are autocorrelated. Figure 2a thus highlights a time window centered between day -1 and day 0 and ranging from day -3 to day $+2$ when precipitation is clearly higher than usual. We identify it as the time range when the flood-producing weather situations generate high precipitation. Two more PAPs are thus defined which range back to 3 days before floods in order to capture precipitation associated with longer-lasting weather events (periods D0-3 and D2-3). The “precursor antecedent precipitation” (PRE-AP) is subsequently defined as the period finishing 4 days before floods. PAPs representing PRE-AP are D4-6, D4-14 and D4-30. To complete the set of PAPs, a similar separation is also applied to APIs (see API2 and API4, stopped 2 and 4 days before floods, respectively). Hereafter, the analysis is based on seasonal percentiles of the PAPs. For comparison, precipitation sums [mm] corresponding to percentiles of different PAPs are shown in Fig. 3. For example, the P99.9 of D0-1 in summer is summarized for all Macro catchments by the rightmost orange boxplot in Fig. 3a. The P99.9 exceeds 94 mm for 50 % of the Macro catchments and reaches 156 mm at one catchment. The P99.9 of D0-1 at Macro catchments is in general lower in winter than in summer (compare the orange and the blue boxplot).

In hydrology, “antecedent precipitation” typically implies all the precipitation preceding the very last flood-triggering event. Here we separate flood-preceding precipitation into the short-range antecedent precipitation and what we define as the precursor antecedent precipitation PRE-AP. Although this sharp separation (between days -3 and -4) is only based on averaged statistics and although flood-triggering events can be defined over a wide range of time scales; we choose this simple formulation to distinguish explicitly long range antecedent precipitation from a period when unusual precipitation is obvious in rainfall time series. We strongly emphasize that hereafter PRE-AP excludes the last 3 days before floods.

4.2 Overview of the precipitation associated with Swiss floods

We start the analysis with an overview of the variability of the precipitation associated with Swiss floods (event and pre-event precipitation).

4.2.1 The 2 days precipitation

Figure 4 shows the 2 day PAP (D0-1) associated with each annual maximum discharge (HQ) of each catchment. The return periods of D0-1 vary by several orders of magnitude between different events. Extreme or very intense precipitation (return period > 100 days) is frequently associated with floods, but a majority of catchments also experience HQs during low or moderate D0-1. A return period < 10 days corresponds to a percentile < P90 and thus to less than 20–30 mm in 2 days (see Fig. 3a and d). There are more floods without intense D0-1 in Nival and Glacial regimes as compared to the Pluvial regime. The D0-1 in Jurassien and Meridional groups is comparable to the Pluvial group. D0-1 is slightly lower in Macro catchments and clearly the weakest for Lakes Exits. HQ5s and HQ20s tend to be associated with longer return periods of D0-1 than HQs, although they can also be triggered by non-intense precipitation (return periods of less than 10 days), especially at Lakes Exits, as well as in Glacial and Nival catchments. Interestingly, extreme D0-1s often occur simultaneously in several catchments, indicating widespread events. Most of them correspond to extraordinary flood events in 1978, 1987, 1990, 1999, 2002, 2005, and 2007 and involve several HQ20s.

4.2.2 Precursor antecedent precipitation

Figure 5 is similar to Fig. 4 but shows the PAP D4-14, i.e. the accumulated precipitation between day –4 and day –14 (PRE-AP). The large majority of floods are associated with return periods of PRE-AP lower than 10 days, i.e. not unusually wet. In general HQ5s and HQ20s are not associated with higher PRE-AP than HQs and the rare cases of unusually wet PRE-AP typically occur simultaneously at many catchments (like in 1972, 1993, 1999 and 2006).

The logarithmic scale of return periods in Figs. 4 and 5 underlines the fact that return periods of D4-14 are several orders of magnitude lower than those of D0-1. However, one cannot expect D4-14 to be systematically extreme as this 11 day period often ex-

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cludes the heavy precipitation (which happens just before the flood). We will now move on to further quantify these qualitative observations.

4.3 Quantification of the precipitation intensity during different periods preceding Swiss floods

5 The overview of flood-precipitation in the last 50 years revealed that precipitation during PAP D0-1 was intense or extreme for a majority of floods but PRE-AP (during PAP D4-14) was not. This raises the question of whether D4-14, although not extreme before floods, still tends to be wetter than climatology.

10 Figure 6 shows the distribution of PAPs for different flood samples (deviations from climatology significant at the 99 % level are outside of the gray zones).

15 For HQ5 s in Micro catchments (Fig. 6a), precipitation during D0-1 was very intense ($> P99$) for 61 % of the floods and intense ($> P90$) for 90 % of the events (6 % $P90-95$ +23 % $P95-99$ +61 % $> P99 = 90 \% > P90$). Only 10 % of the floods were preceded by no or moderate precipitation ($< P90$). For D2-3, intense and very intense precipitation was also significantly more frequent than usual although the deviation from climatology is very weak compared to D0-1. Drier percentiles were also significantly less frequent than usual (only 35 % $< P50$). On the other hand, no significant departure from climatology is found for the PRE-AP PAPs (D4-6, D4-14, D4-30). This means that, as a general rule, the conditions were not significantly wetter than usual earlier than 3 days before floods in Micro catchments.

20 The statistics of Meso and Macro catchments (Fig. 6b and c) resemble the ones of Micro catchments.

25 In contrast, HQ5 s at Lakes Exits (Fig. 6d) were triggered by significantly higher than usual precipitation during all PAPs (and not only during D0-1 and D2-3). For example, the $P > 99$ of D4-14 is as frequently observed as $P < 50$.

Figure 6e and f shows the results for HQs and HQ20 s in all catchments. During D0-1, very intense precipitation is twice as frequent prior to HQ20 s (80 % of all floods) as it is prior to all annual HQs (45 % of all floods). However, the precipitation prior to HQs

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and HQ20 s is surprisingly similar during the other periods (D2-3 is only slightly higher for HQ20 s than for HQs and PRE-AP is basically the same).

In summary, the flood events considered in this study, with the exception of Lakes Exit floods, frequently co-occur with intense precipitation during the flood day and/or the day before (D0-1). Longer-lasting multi-day events also generate high precipitation during D2-3. The slightly larger departure from climatology during D2-3 at Marco compared to Micro catchments indicates a higher importance of longer-lasting events. Helbling et al. (2006) already showed that larger catchments are more sensitive to longer-lasting precipitation at the sub-daily scale; here we can extend those findings to multi-day events. Regarding precipitation 4 or more days before HQ days, a significantly enhanced frequency of wet weeks is only found for Lakes Exits. For other catchments, floods did not happen after significantly wetter nor drier PRE-AP in general.

Although no significant signal is found, PRE-AP was nevertheless slightly wetter than climatology before floods in Switzerland. Consequently, more detailed analyses are presented in the next sections to explore the correlation between PRE-AP and floods for particular catchments, particular flood types, and particular flood seasons.

4.4 Catchment by catchment analysis

Here, we use logistic regression to address the following question for each PAP and each catchment: is the occurrence of HQs influenced by the amount of precipitation? Or in other words: are floods more (or less) frequent after wet periods? We thereby aim to investigate whether the large variety of Swiss basins is associated with different flood responses to PAPs. Previous studies showed that typical flood-triggering precipitation depends not only on catchment size (investigated in the previous section), but also on various catchment properties (e.g. Merz and Blöschl, 2003; Weingartner et al., 2003; Helbling et al., 2006; Diezig and Weingartner, 2007). Potentially important properties include mean elevation, slope, land cover, soil type, geology and reservoirs (lakes, underground cavities). The hydrological regimes encompass some of this variability and serve as a framework for interpreting the following analysis.

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Figure 7 shows the results of the logistic regression for the different PAPs (see details in Sect. 3.4). For example, triangles (P value < 0.001) in Fig. 7a indicate that, in every catchment investigated, floods were significantly more frequent when a particular threshold of D0-1 was exceeded. In other words, the amount of precipitation that falls during D0-1 has a significant impact on flood frequency. The amount of precipitation that falls during D2-3 (Fig. 7b) also significantly impacts the flood frequency in most catchments, with the exception of most Glacial and few Nival and Pluvial catchments. With regard to PRE-AP in D4-6, D4-14 and D4-30 (Fig. 7c–e), clear regional patterns can be distinguished. Wet antecedent periods significantly enhance the flood frequency mainly in the northwest and northeast Switzerland, as well as at the exit of all lakes except Lake Thun (nb. 111). In contrast, floods were significantly less frequent after wet periods in some Glacial catchments. Indeed, six catchments show a significant P value with an odd ratio smaller than 1 for D4-14. These are the exact 6 catchments with more than 25 % glacial coverage. For the rest of Switzerland, the amount of PRE-AP does not significantly affect the flood probability. By comparing the results of D0-30 with D4-30, it emerges that floods are significantly associated with wet months (D0-30) in a large majority of catchments only because heavy precipitation 3–4 days before floods lead to high monthly accumulations. Indeed, D4-30 indicates that precipitation during the rest of the month has no significant impact on the flood probability for most catchments.

A reduced flood frequency following wet periods (like found for the glacial catchments) seems counterintuitive. The most significant negative correlation is found for the most glaciated catchment (the Aletsch glacier catchment, nb. 865). The highest significance is obtained in this case with the threshold P75 because none of the 51 HQs recorded correspond to the 25 % wettest D4-14. The expected value is 51/4; i.e. approximately 12–13 HQs. It is almost impossible to get 0 HQs just by chance and an explanation must therefore be found. Glacial catchments are typically small and located at high elevations, exhibit steep slopes and lack deep soils. They are characterized by very short response times and a large runoff contribution from melt during

the flood season (summer, see e.g. Verbunt et al., 2003; Köplin et al., 2014). The negative correlation is probably due to the fact that prolonged periods of wet weather (lower temperature, reduced sunshine and hence reduced melt) can lead to a lower baseflow in those catchments so that contributions from short and intense precipitation events would be less likely to generate annual discharge peaks. Indeed, discharge time series of glacial catchments are typically characterized by a pronounced diurnal cycle in summer, revealing the importance of high temperature and sunshine for melt and discharge generation. The baseflow continuously rises from day to day in case of extended periods of nice weather which are therefore particularly conducive to floods.

Enhanced flood frequency after wet periods is less surprising. The Swiss Plateau, especially the western part, is a relatively flat area characterized by deep soils that need to be saturated before large runoff in the main streams is recorded. Soils in the Jura are typically thinner but very permeable and this region is well known for its underground karstic cavities. A karstic underground network can contain important reservoirs, the water level of which influences the flow response in surface streams (see e.g. Ball and Martin, 2012).

In summary, the role of long-term antecedent precipitation for flood generation depends strongly on the region and/or on the hydrological regime considered. Wet PRE-AP periods enhance HQ probability where soil saturation and reservoir filling are important processes and decrease HQ probability where melt water is an important contributor to the floods discharges.

4.4.1 Antecedent precipitation indices (APIs)

We also tested the power of APIs (see Table 1) for statistically predicting floods as compared to simple precipitation sums. API2, like D2-3, omits information about the flood day and the day preceding the flood but accounts for the whole antecedent precipitation instead of for only 2 days. The results for both periods are similar in most catchments. D2-3 is a better (more significant) flood predictor than API2 for 12 catchments, and a weaker predictor for 11 catchments. API2 allows us to distinguish the relevance of

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dry periods for flooding in Glacial catchments but D2-3 is too short and too close to the flood to capture this signal. However, combining D2-3 and D4-6 indicates that dry conditions followed by wet conditions are important for flood formation in the Lütshine in Gsteig (nb. 387), for example. Both periods cancel out in API2 and no significant signal is found. Searching for the best period also appears to be complex with regard to PRE-AP. Each of the 4 periods (D4-6, D4-14, D4-30, API4) is the most significant flood predictor at several catchments. D4-30 is rarely the best predictor, indicating that the precipitation sum over a monthly period is not a powerful measure for flood probability. API4 is slightly more often a better measure than D4-6 and D4-14, although this is not systematic. APIs are widely used in hydrology (see e.g. Kohler and Linsley Ray, 1951; Fedora and Beschta, 1989; Heggen, 2001; Trambly et al., 2012) but our integrative study cannot confirm that they explain flood frequency better than simple precipitation sums.

4.5 Impacts of short range precipitation and PRE-AP on flood magnitude

In the previous sections, the impact of PAPs on HQ probability was discussed (i.e. whether floods are more frequent after wet periods). Here, the impact on the flood magnitude is investigated as well (i.e. whether larger floods follow wetter periods than smaller floods).

In Fig. 8, the flood-precipitation is simply summarized by the median return period of the PAPs for a flood sample. This allows us to compare various flood samples (different flood magnitudes, different catchment groups, different flood seasons). Assuming that the precipitation distribution is equal to climatology before floods, the median return period should be equal to 2 days (delimited by solid lines in the graphs).

For the Micro, Meso and Macro catchments in Fig. 8a, larger floods correspond to higher D0-1 than smaller floods (HQ20s are associated with a median return period of D0-1 of 400–1000 days = 1–3 years while HQ1s correspond to a median D0-1 of only 60 days). In contrast, HQ20s are related to clearly higher D2-3 only at Macro catchments. At those catchments, as much precipitation falls 2 to 3 days before the

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HQ20 s as falls 0 to 1 days before all HQs. At Lakes Exits, D2-3 is more extreme than D0-1 because of the long time delay between precipitation and gauged discharge (see Sect. 4.1).

Figure 8a can be directly compared to Fig. 8b. For Micro, Meso and Macro catchments, the return periods of D0-3 in Fig. 8b are similar to the ones of D0-1. On the other hand, the median PRE-AP is remarkably close to normal for each catchment size (close to the climatological median). Moreover, the PRE-AP was not higher before HQ20 s than before HQ1 s. A change in PRE-AP with flood magnitude is only found at Lakes Exits.

Figure 8c–f investigates different hydrological regimes and different flood seasons. For no regime and no season is the amount of PRE-AP precipitation linked to the flood amplitude. Even at Jurassien catchments, where we found that floods are significantly more frequent after wet periods, HQ20 s are not associated with wetter periods than HQ1 s.

4.6 Can weaker precipitation trigger floods if PRE-AP is higher?

In the previous sections, the PAPs were investigated separately. Here we show the combinations of PRE-AP and short-range precipitation events for single floods. If the runoff coefficient is enhanced by wetter PRE-AP (and thus more saturated soils), floods might happen in association with weaker triggering events.

Figure 9 shows D0-3 and D4-14 of all flood events for different catchment samples. As already inferred from Fig. 4, precipitation accumulations before floods vary remarkably between single events and the portion of floods lacking intense triggering precipitation is highest in Glacial and Nival catchments. The green lines in Fig. 9 show the linear regression between D0-3 and D4-14 for HQ5 events (only HQ5 s are shown for clarity). The regression lines address the following question: did wet periods of PRE-AP allow weaker weather events to generate HQ5s? Indeed, it seems that for the Jurassien, Meridional and Lakes Exit catchments, HQ5 s that were triggered by weaker weather events tend to be associated with higher values of PRE-AP. This is in contrast

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to Glacial catchments where weaker events trigger HQ5 s after drier periods. Regarding flood forecasting, it would be interesting to define a minimum threshold: what amount of event precipitation is required to trigger a HQ5 given that PRE-AP is known? The scatter in observations shows that defining such a threshold is impossible for Switzerland because floods can occur in association with all types of precipitation. The only flood sample for which such a threshold would be realistic is the set of HQ20 s at Lakes Exits. There, a HQ20 occurred without precipitation in the last 3 days but after an exceptionally wet period of PRE-AP. In contrast, all HQ20 s occurring after not unusually wet periods of PRE-AP required at least a D0-3 of return period of 100 days. There might be a minimum threshold of D0-3 for HQ20 s in Macro and Meridional catchments as well but it does not seem to depend on PRE-AP.

5 Discussion

Our results are based on a synoptic and statistical approach that emphasizes the common signature of antecedent precipitation to a large sample of flood events in Switzerland. In this section, we comment on the specific limitations of this approach and of our data and put our results in the context of previous work.

We call weekly to monthly precipitation periods preceding floods by more than 3 days “PRE-AP” (PREcursor Antecedent Precipitation) periods. The comprehensive statistical analysis shows that the occurrence of annual floods is differently related to PRE-AP in different regions. (i) Annual floods are significantly more frequent after wet PRE-AP periods in most Jurassien catchments, in some Pluvial catchments of northwestern and northeastern Switzerland, and at lakes exits. (ii) Annual floods are significantly less frequent after wet PRE-AP periods in glacial catchments. (iii) The amount of PRE-AP is not significantly related to the occurrence of annual floods in the rest (the majority) of Swiss catchments. Also, PRE-AP is absolutely not related to flood magnitude except at lakes exits (for all catchment sizes, all hydrological regimes and during all seasons). The precipitation outside of a 4 day period is not related to the amplitude of discharge

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for the occurrence and amplitude of peak discharges in the different Swiss hydrological regions.

6 Conclusions

We quantify statistically the influence of different precipitation periods for the generation of thousands of annual floods in Switzerland. In contrast to previous studies that define antecedent precipitation as all the water that fell before the very last flood-triggering precipitation event, we explicitly separate antecedent precipitation into the short-range and long-range antecedent precipitation based on the autocorrelation of daily precipitation time series and reflecting the synoptic time scale. The short-range encompasses the 0–3 days period before floods and the long range the earlier period (called PRE-AP). This novel distinction allows to specifically address the role of several antecedent precipitation periods for flood generation.

At the short range, we do not separate antecedent precipitation from the precipitation event directly triggering the discharge peak. Instead, we consider accumulations over several days and address the following question: over which preceding period is the amount of precipitation related to flood frequency and flood magnitude?

The 2 day sum (0–1 days before floods) is clearly the best correlated with both the flood frequency and the flood magnitude. The precipitation 2 to 3 days before floods also significantly affects flood frequency everywhere except in the high Alps. It is more over related to flood magnitude at lakes exits and in large catchments. Regarding earlier periods however, we find that PRE-AP has had no significant impact on flood frequency for the majority of Swiss catchments in the last 50 years. Moreover, the magnitude of floods was also independent on the magnitude of PRE-AP in all catchment types except at lakes exits. The influence of PRE-AP is thus overall weak. We thus suggest that researchers focus on 2 to 4 days precipitation periods when reconstructing antecedent precipitation of past Alpine floods or when inferring future Alpine flood risk from climate projections. Long range antecedent precipitation periods preceding

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Table 3. Summary of catchment properties for the selected stations. Catchments are sorted based on hydrological regime and increasing size from top to bottom. Locations are given in Swiss coordinates (CH1903).

Number	Name	coord X	coord Y	Area [km ²]	Station Height [m]	Avg. Height [m]	Glacier coverage [%]	Hydro. Regime
844	Ferreraabach – Trun	717 795	179 550	12.5	1220	2461	17.3	Glacial
821	Alpbach – Erstfeld. Bodenberg	688 560	185 120	20.6	1022	2200	27.7	Glacial
945	Rein da Sumvitg – Sumvitg. Encardens	718 810	167 690	21.8	1490	2450	6.7	Glacial
751	Gornernbach – Kiental	624 450	155 130	25.6	1280	2270	17.3	Glacial
838	Ova da Cluozza – Zernez	804 930	174 830	26.9	1509	2368	2.2	Glacial
803	Witenwasserrenneuss – Realp	680 950	160 130	30.7	1575	2427	12.7	Glacial
735	Simme – Oberried/Lenk	602 630	141 660	35.7	1096	2370	34.6	Glacial
792	Rhone (Rotten) – Gletsch	670 810	157 200	38.9	1761	2719	52.2	Glacial
1250	Goneri – Oberwald	670 520	153 830	40	1385	2377	14.2	Glacial
753	Kander – Gasterntal. Staldi	621 080	144 260	40.7	1470	2600	43.5	Glacial
848	Dischmabach – Davos. Kriegsmatte	786 220	183 370	43.3	1668	2372	2.1	Glacial
740	Hinterrhein – Hinterrhein	735 480	154 680	53.7	1584	2360	17.2	Glacial
778	Rosegbach – Pontresina	788 810	151 690	66.5	1766	2716	30.1	Glacial
922	Chamuerabach – La Punt-Chamues-ch	791 430	160 600	73.3	1720	2549	1.5	Glacial
793	Lonza – Blatten	629 130	140 910	77.8	1520	2630	36.5	Glacial
782	Berninabach – Pontresina	789 440	151 320	107	1804	2617	18.7	Glacial
1064	Poschiavino – Le Prese	803 490	130 530	169	967	2170	6.5	Glacial
865	Massa – Blatten bei Naters	643 700	137 290	195	1446	2945	65.9	Glacial
387	Lütschine – Gsteig	633 130	168 200	379	585	2050	17.4	Glacial
890	Poschiavino – La Rôsa	802 120	142 010	14.1	1860	2283	0.35	Nival
765	Krummbach – Klusmatten	644 500	119 420	19.8	1795	2276	3	Nival
948	Chli Schliere – Alpnach. Chilch Erli	663 800	199 570	21.8	453	1370	0	Nival
750	Allenbach – Adelboden	608 710	148 300	28.8	1297	1856	0	Nival
799	Grosstalbach – Isenthal	685 500	196 050	43.9	767	1820	9.3	Nival
826	Ova dal Fuorn – Zernez. Punt la Drossa	810 560	170 790	55.3	1707	2331	0.02	Nival
822	Minster – Euthal. Rüti	704 425	215 310	59.2	894	1351	0	Nival
916	Taschinasbach – Grünsch. Wasserf.Lietha	767 930	206 420	63	666	1768	0.04	Nival
862	Saltina – Brig	642 220	129 630	77.7	677	2050	5.1	Nival
852	Thur – Stein. Ittishag	736 020	228 250	84	850	1448	0	Nival
720	Grande Eau – Aigle	563 975	129 825	132	414	1560	1.8	Nival
1143	Engelberger Aa – Buochs. Flugplatz	673 555	202 870	227	443	1620	4.3	Nival
1017	Plessur – Chur	757 975	191 925	263	573	1850	0	Nival
284	Muota – Ingenbohl	688 230	206 140	316	438	1360	0.08	Nival
637	Simme – Oberwil	600 060	167 090	344	777	1640	3.7	Nival
1117	Kander – Hondrich	617 790	168 400	496	650	1900	7.9	Nival
1127	Landquart – Felsenbach	765 365	204 910	616	571	1800	1.4	Nival
1252	Sellenbodenbach – Neuenkirch	658 530	218 290	10.5	515	615	0	Pluvial
882	Steinbach – Kaltbrunn. Steinbrugg	721 215	229 745	19.1	451	1112	0	Pluvial
831	Steinach – Steinach	750 760	262 610	24.2	406	710	0	Pluvial
1240	Biber – Biberbrugg	697 240	223 280	31.9	825	1009	0	Pluvial
932	Sionge – Vuippens. Château	572 420	167 540	45.3	681	862	0	Pluvial
1251	Alp – Einsiedeln	698 640	223 020	46.4	840	1155	0	Pluvial
833	Aach – Salmisach. Hungerbühl	744 410	268 400	48.5	406	480	0	Pluvial
1022	Goldach – Goldach	753 190	261 590	49.8	399	833	0	Pluvial
789	Bibere – Kerzers	581 280	201 850	50.1	443	540	0	Pluvial
1118	Rot – Roggwil	630 260	231 650	53.6	436	586	0	Pluvial
1128	Gürbe – Burgistein. Pfandersmatt	605 890	181 880	53.7	569	1044	0	Pluvial
863	Langelen – Huttwil. Häberenbad	629 560	219 135	59.9	597	766	0	Pluvial
1231	Worbte – Ittigen	603 005	202 455	60.5	522	679	0	Pluvial
1151	Veveysse – Vevey. Copet	554 675	146 565	62.2	399	1108	0	Pluvial

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Table 3. Continued.

Number	Name	coord X	coord Y	Area [km ²]	Station Height [m]	Avg. Height [m]	Glacier coverage [%]	Hydro. Regime
834	Urnäsch – Hundwil, Äschentobel	740 170	244 800	64.5	747	1085	0	Pluvial
528	Murg – Wängi	714 105	261 720	78.9	466	650	0	Pluvial
1066	Lorze – Baar	683 300	228 070	84.7	455	866	0	Pluvial
911	Necker – Mogelsberg, Aachsäge	727 110	247 290	88.2	606	959	0	Pluvial
1140	Lorze – Zug, Letzi	680 600	226 070	101	417	825	0	Pluvial
898	Mentue – Yvonand, La Mauguettaz	545 440	180 875	105	449	679	0	Pluvial
888	Langeten – Lotzwil	626 840	226 535	115	500	713	0	Pluvial
650	Gürbe – Belp, Mülimatt	604 810	192 680	117	522	837	0	Pluvial
977	Murg – Frauenfeld	709 540	269 660	212	390	580	0	Pluvial
549	Töss – Neftenbach	691 460	263 820	342	389	650	0	Pluvial
978	Sense – Thörishaus, Sense matt	593 350	193 020	352	553	1068	0	Pluvial
962	Wigger – Zofingen	637 580	237 080	368	426	660	0	Pluvial
883	Broye – Payerne, Caserne d'aviation	561 660	187 320	392	441	710	0	Pluvial
938	Glatt – Rheinsfelden	678 040	269 720	416	336	498	0	Pluvial
1100	Emme – Emmenmatt	623 610	200 420	443	638	1070	0	Pluvial
944	Kleine Emme – Littau, Reussbühl	664 220	213 200	477	431	1050	0	Pluvial
825	Thur – Jonschwil, Mühlau	723 675	252 720	493	534	1030	0	Pluvial
854	Bied du Lochle – La Rançonnière	545 025	211 575	38	819	NA	NA	Jurassien
1254	Scheulte – Vicques	599 485	244 150	72.8	463	785	0	Jurassien
959	Aubonne-Allaman, Le Coulet	520 720	147 410	91.4	390	890	0	Jurassien
1173	Promenthouse – Gland, Route Suisse	510 080	140 080	100	394	1037	0	Jurassien
972	Seyon – Valangin	559 370	206 810	112	630	970	0	Jurassien
829	Suze – Sonceboz	579 810	227 350	150	642	1050	0	Jurassien
946	Dünneren – Olten, Hammermühle	634 330	244 480	196	400	750	0	Jurassien
1150	Allaine – Boncourt, Frontière	567 830	261 200	215	366	559	0	Jurassien
960	Venoge-Ecublens, Les Bois	532 040	154 160	231	383	700	0	Jurassien
915	Ergolz – Liestal	622 270	259 750	261	305	590	0	Jurassien
1139	Areuse – Boudry	554 350	199 940	377	444	1060	0	Jurassien
380	Birs – Münchenstein, Hofmatt	613 570	263 080	911	268	740	0	Jurassien
879	Riale di Calneggia – Caveragno, Pontit	684 970	135 960	24	890	1996	0	Meridional
975	Magliasina – Magliaso, Ponte	711 620	93 290	34.3	295	920	0	Meridional
1255	Riale di Pincascia – Lavertezzo	708 060	123 950	44.4	536	1708	0	Meridional
871	Breggia – Chiasso, Ponte di Polenta	722 315	78 320	47.4	255	927	0	Meridional
843	Cassarate – Pregassona	718 010	97 380	73.9	291	990	0	Meridional
1287	Vedeggio – Agno	714 110	95 680	105	281	898	0	Meridional
769	Calancasca – Buseno	729 440	127 180	120	746	1950	1.1	Meridional
1241	Verzasca – Lavertezzo, Campi	708 420	122 920	186	490	1672	0	Meridional
67	Ticino – Bellinzona	721 245	117 025	1515	220	1680	0.7	Macro
785	Inn – Tarasp	816 800	185 910	1584	1183	2390	5.1	Macro
136	Thur – Andelfingen	693 510	272 500	1696	356	770	0	Macro
764	Limmat – Baden, Limmatpromenade	665 640	258 690	2396	351	1130	1.1	Macro
51	Reuss – Mellingen	662 830	252 580	3382	345	1240	2.8	Macro
942	Rhein – Bad Ragaz, ARA	757 090	209 600	4455	491	1930	1.9	Macro
32	Rhône – Porte du Scex	557 660	133 280	5244	377	2130	14.3	Macro
47	Aare – Brugg	657 000	259 360	11 726	332	1010	2	Macro
527	Lorze – Frauenthal	674 715	229 845	259	390	690	0	Lake Exit
656	Tresa – Ponte Tresa, Rocchetta	709 580	92 145	615	268	800	0	Lake Exit
377	Linth – Weesen, Biäsche	725 160	221 380	1061	419	1580	2.5	Lake Exit
917	Reuss – Luzern, Geissmattbrücke	665 330	211 800	2251	432	1500	4.2	Lake Exit
111	Aare – Thun	613 230	179 280	2466	548	1760	9.5	Lake Exit
1253	Rhône – Genève, Halle de l'île	499 890	117 850	7987	369	1670	9.4	Lake Exit
1170	Aare – Brugg, Ägerten	588 220	219 020	8293	428	1150	2.9	Lake Exit

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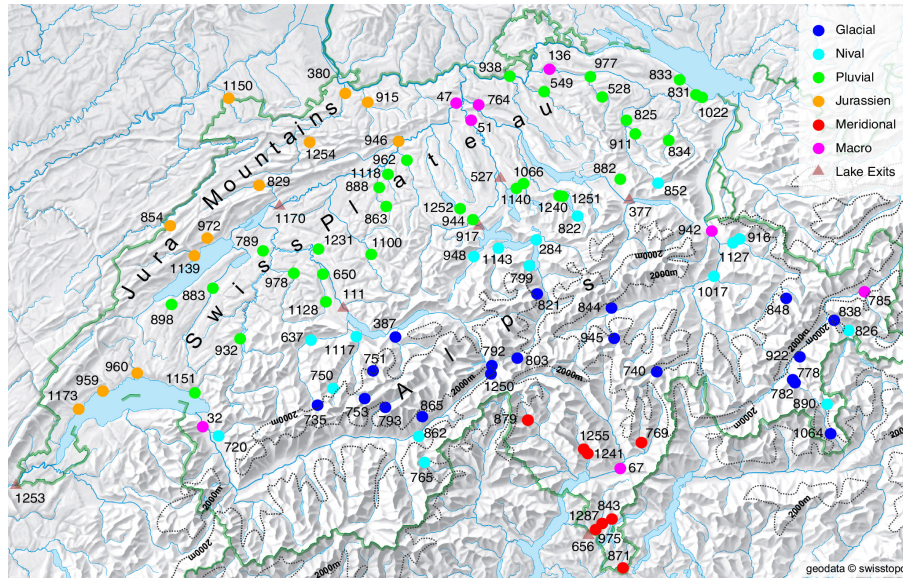


Figure 1. Swiss river discharge stations selected for this study. Colors refer to the hydrological regimes in the legend. Stations at lakes exits are shown by triangles to highlight the strong anthropogenic influence on the discharge (lakes exits are thus analyzed separately). The numbers refer to Table 3 which provide brief descriptions of the catchments.

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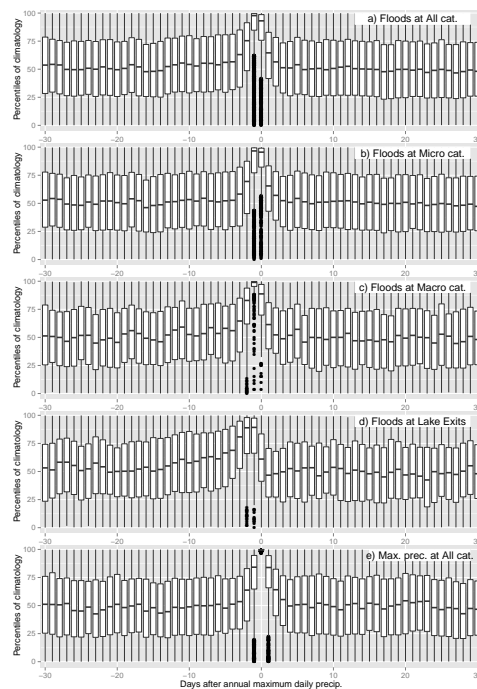


Figure 2. The distribution of daily precipitation before and after all flood events is shown in **(a)**. For example, the boxplot at $x = -10$ represents the distribution of daily precipitation percentiles 10 days prior to the 4257 annual flood events analyzed in this study (all HQs from all catchments). The middle line of the boxplots shows the median, the boxes comprise the 25–75 percentile range, and the whiskers end at a deviation from the mean of 1.5 the interquartile range. **(b–d)** Same as **(a)** but for floods in Micro catchments, Macro catchments and lakes exits. **(e)** The same procedure as in **(a)**, but applied to annual maximum precipitation days instead of annual flood days.

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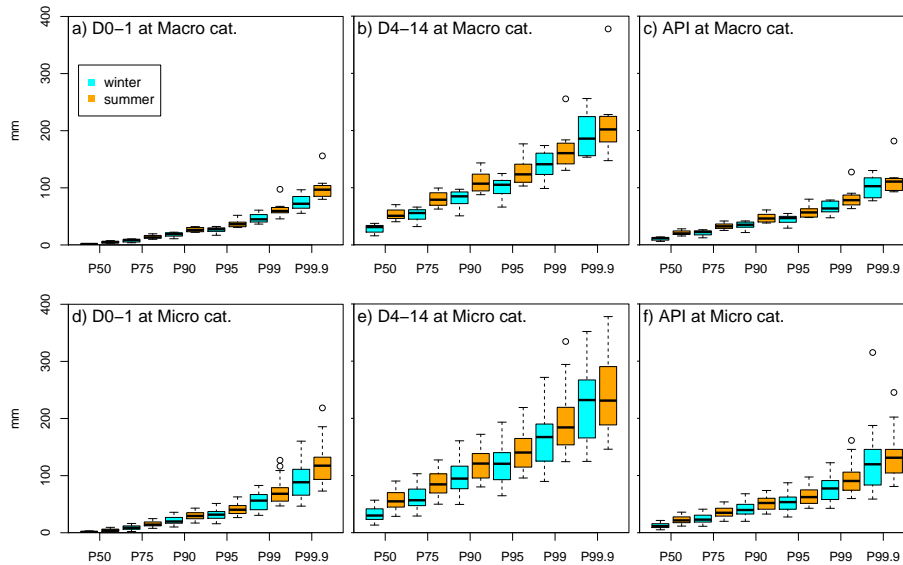


Figure 3. Absolute values of the climatological percentiles for the different PAPs. Statistics from Macro (a–c) and Micro (d–f) catchments are shown on the top and bottom row, respectively. Accumulations over 2 days which correspond to the PAPs D0-1 or D2-3 are shown in (a, d). Accumulations over 11 days corresponding to D4-14 are shown in (b, e). APIs are shown in (c, f).

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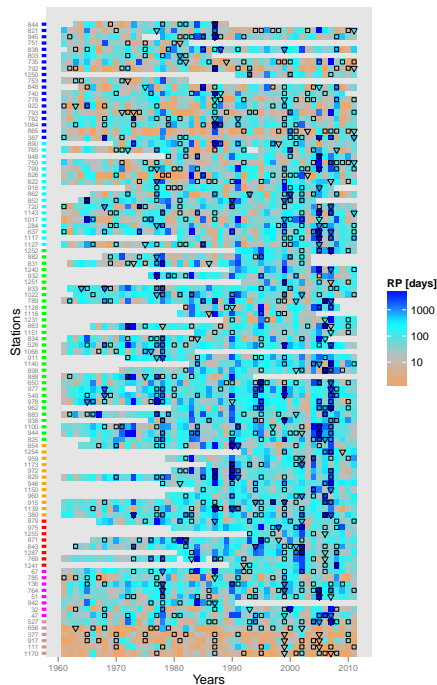


Figure 4. Overview of all flood events. All river discharge stations (numbers on the y axis, see Table 3) cover at least 20 years in the 1961–2011 period. For each annual discharge peak, the return period of the two-days precipitation sum (D0-1) is indicated by colors. HQ5s and HQ20s are marked with squares and triangles, respectively. The catchments are sorted by regime type and by increasing size from top to bottom. Hydrological regimes are indicated by colors: blue = Glacial, cyan = Nival, green = Pluvial, orange = Jurassien, red = Meridional, magenta = Macro, brown = Lakes Exits.

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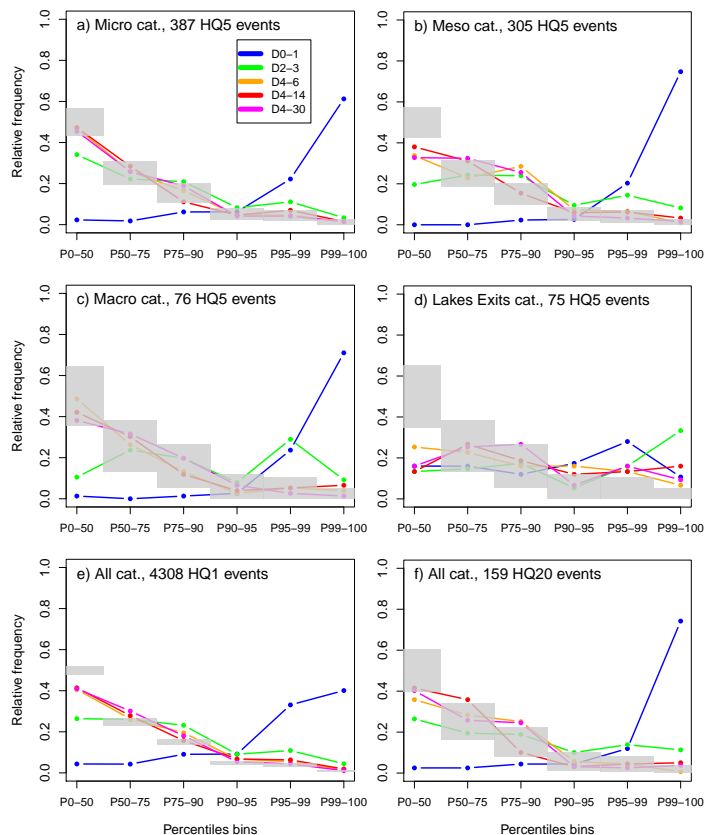


Figure 6. Relative frequency of precipitation percentiles for several PAPs before floods. Each colored line represents a PAP. **(a–d)** HQ5s in **(a)** Micro catchments, **(b)** Meso catchments, **(c)** Macro catchments and **(d)** Lakes Exits catchments. **(e)** All HQs and **(f)** HQ20s in all catchments. Gray shadings represent the 99 % level of significance of the frequency of each percentile bin.

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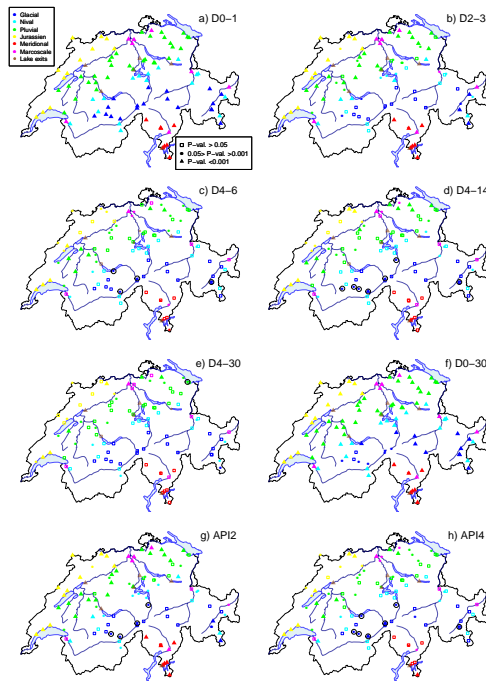


Figure 7. The relevance of the different precipitation periods for the occurrence of annual floods is tested using logistic regression (**a**) D0–1, (**b**) D2–3, (**c**) D4–6, (**d**) D4–14, (**e**) D4–30, (**f**) D0–30, (**g**) API2, and (**h**) API4. For each precipitation period and each catchment, the following question is addressed using logistic regression: does the exceedance of a given precipitation threshold significantly change the flood probability? Several thresholds are tested (P50, P75, P90, P95, P99) and the most significant P value is displayed symbolically (squares, dots and triangles indicate a non-, weakly-, and strongly-significant influence, respectively). The colors of the symbols refer to the hydrological regimes of the catchments. Circles denote a negatively significant correlation, i.e. the exceedance of a given precipitation threshold significantly reduces flood probability. Negative correlations are almost exclusively found in Glacial catchments.

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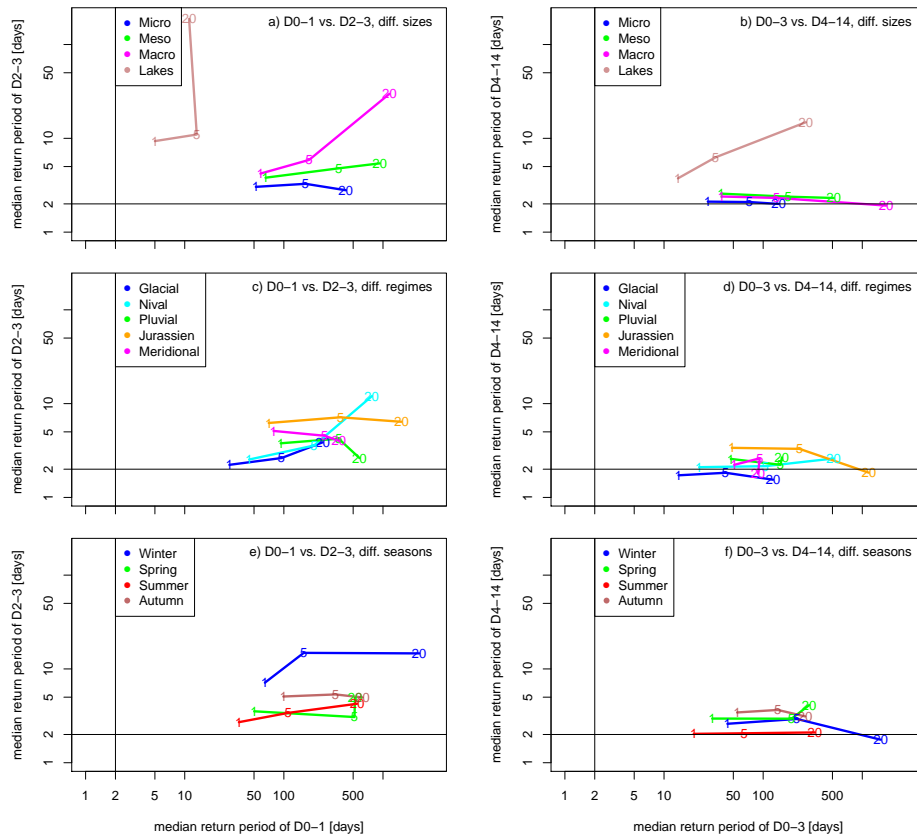


Figure 8. Median return periods of flood-associated precipitation for different flood samples. The rows show different catchment sizes (**a**, **b**), different hydrological regimes (**c**, **d**) and different flood seasons (**e**, **f**). The left column shows D0-1 in x and D2-3 in y and the right column D0-3 in x and D4-14 in y . The numbers 1, 5 and 20 indicate median return periods associated with all HQs, with all HQ5s, and with all HQ20s, respectively. They are joined together by a line.

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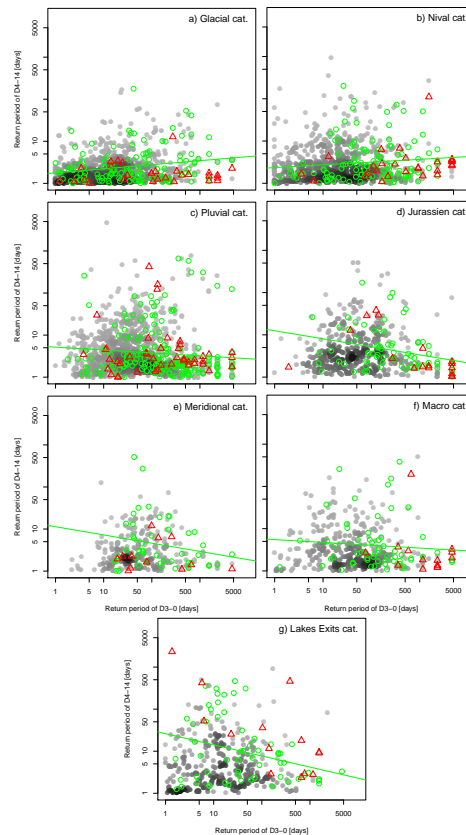


Figure 9. Flood-associated precipitation for different catchment samples: **(a)** Glacial, **(b)** Nival, **(c)** Pluvial, **(d)** Jurassien, **(e)** Meridional, **(f)** Macro and **(g)** Lakes Exits. For each discharge peak, D0-3 is shown in x and D4-14 in y . Annual floods are shown by gray dots (shadings indicate the density of dots), HQ5s by green dots and HQ20s by red triangles. Green lines show the linear regression of the HQ5s.

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