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Effective precipitation duration for runoff peaks based on catchment modelling

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ABSTRACT

Despite precipitation intensities may greatly vary during one flood event, detailed information about these intensities may not be required to accurately simulate floods with a hydrological model which rather reacts to cumulative precipitation sums. This raises two questions: to which extent is it important to preserve sub-daily precipitation intensities and how long does it effectively rain from the hydrological point of view? Both questions might seem straightforward to answer with a direct analysis of past precipitation events but require some arbitrary choices regarding the length of a precipitation event. To avoid these arbitrary decisions, here we present an alternative approach to characterize the effective length of precipitation event which is based on runoff simulations with respect to large floods. More precisely, we quantify the fraction of a day over which the daily precipitation has to be distributed to faithfully reproduce the large annual and seasonal floods which were generated by the hourly precipitation rate time series. New precipitation time series were generated by first aggregating the hourly observed data into daily totals and then evenly distributing them over sub-daily periods (n hours). These simulated time series were used as input to a hydrological bucket-type model and the resulting runoff flood peaks were compared to those obtained when using the original precipitation time series. We define then *the effective daily precipitation duration* as the number of hours n, for which the largest peaks are simulated best. For nine mesoscale Swiss catchments this effective daily precipitation duration was about half a day, which indicates that detailed information on precipitation intensities is not necessarily required to accurately estimate peaks of the largest annual and seasonal floods. These findings support the use of simple disaggregation approaches to make usage of past daily precipitation observations or daily precipitation simulations (e.g. from climate models) for hydrological modeling at an hourly time step.

1. Introduction

Switzerland is a country with high flood risk, especially in its mountainous areas where a number of factors connected to topography and relief lead to a continually high disposition for floods (Weingartner et al., 2003). In addition, the damage potential has multiplied over the past decades due to an increase in built-up areas and extensive construction activity. According to the Swiss Confederation Swiss Federal Council (2016), about 20% of Switzerland's population, 25% of its material assets and 30% of its workplaces are situated in flood prone areas. Total flood losses in the years 1972–2014 amounted to an annual mean of 270 Mio EUR (Andres et al., 2015). Due to anticipated changes in climate and land cover, even more severe floods are expected in the future in Switzerland (Koplin et al., 2013, 2014; Academies of Arts and Sciences, 2016). The accurate estimation of flood peaks is thus of high importance as a basis for prevention of and protection from flood-related hazards. In this context, not only annual but even more importantly seasonal floods have been shown to lead more frequently to unexpectedly severe flood episodes as a result of human induced changes (European Environment Agency, 2012; Hirsch and Archfield, 2015). Hence, it has been recently recommended that studies of annual extreme floods should be compounded with analysis of seasonal floods (Brunner et al., 2017; Fischer et al., 2016).

Estimation of annual and seasonal flood peaks requires, on the one hand, information on the amount and intensity of the corresponding precipitation event at a temporal scale which is adequate

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to represent the causative processes. On the other hand, assessing possible alterations in flood responses as due to human induced changes implies using a hydrological model that needs to be calibrated with observed precipitation-runoff data. In this respect, one of practical issues that one has to deal with is the feasibility of using observed precipitation data for flood simulations that may require higher resolutions than actually available. Indeed, traditionally and particularly in the 20th century, measurement of precipitation amounts has been restricted to daily totals for practical reasons only (Koutsoyiannis and Onof, 2001; Pui et al., 2012). This is also the case for Switzerland where hourly stations have been regularly operated only since the mid-1980s (Seiz and Foppa, 2007). Another challenge is that one may need to deal with are simulations of future precipitation conditions from climate models which are usually available at daily scales only. Yet, in terms of mesoscale catchments (catchment area of roughly 40–500 km^2), flood generation is assumed to occur at an hourly rather than at a daily scale. Thus daily precipitation totals are usually assumed not to be suited to accurately simulate large flood peaks (Aronica et al., 2005; Wetterhall et al., 2011). If higher resolution of precipitation data is needed, determination of the extent, to which such a sub-daily distribution is necessary for hydrological modelling of large annual and seasonal peaks, is not trivial. A direct way would be to analyze observed precipitation time series and based on these compute the average length of large precipitation events. However such an approach requires taking arbitrary decisions regarding the threshold intensity to use to define the occurrence of the precipitation event, and to decide how long breaks in precipitation are allowed within one precipitation event.

As an alternative, we here propose an approach to characterize the effective length of precipitation events. More precisely, we address the question of which fraction of a day it effectively rains (from a hydrological point of view) when the largest annual and seasonal runoff events are generated. We hypothesize that, as far as flood peaks are considered, the effect of varying precipitation intensities can be assessed in an integrated way by varying the length of a precipitation event of constant precipitation intensities. We speculate that this effect is due to the postponed catchment reaction represented with the time of concentration (Grimaldi et al., 2012) and different (usually mixed) hydrological mechanisms lying behind such large (annual and seasonal) floods represented with distinctive flood-types (Sikorska et al., 2015b; Merz and Bloschl, 2003). While the time of concentration measures how fast the precipitation water needs to travel to the catchment outlet and thus represents catchment storage properties, flood-types synthesize information on major natural processes that have contributed to the flood generation and are not limited to precipitation-driven floods only.

At the first sight this approach may seem similar to the previous studies that identified input rainfall errors from rainfall-runoff data with the help of a hydrological model (e.g. Kavetski et al., 2006a,b; McMillan et al., 2012; Renard et al., 2011; Sikorska et al., 2012; Thyer et al., 2009). Yet, in contrast to these studies, we do not aim at inferring errors in precipitation data or in the model structure. We here focus on the question of how observed daily precipitation totals, with their errors, should be distributed over a day so that the largest flood peaks can be simulated best. To address this issue, a hydrological bucket-type model was used for the simulation of flood peaks with different precipitation hourly time series used as input. We generated new precipitation time series by first aggregating the hourly observed precipitation data into daily totals and then evenly distributing these totals over n hours. These time series are then fed into the hydrological model and the resulting largest runoff peaks are diagnosed according to the magnitude of their under/over-estimation. We then define *the effective daily precipitation duration* as the number of hours n, for which the simulated peaks were closest to those being simulated using the original hourly precipitation time series. (Please note that 'effective' refers to the duration and the term effective daily precipitation duration should not be confused with the term effective precipitation.) As the resulting runoff peak depends largely on how the precipitation total is distributed over time, with runoff peaks decreasing if the same amount is distributed over more hours and increasing vice versa, changes in simulated peak magnitudes can be assigned based on the choice of n. Hence our approach allows a quantification of the effective daily precipitation duration which is interesting for two reasons. Firstly, our approach provides a quantification of catchment behaviour which combines precipitation characteristics and catchment responsiveness in one value. We suggest that this is a useful metric for catchment characterisation. Secondly, this analysis is of practical value as it provides an indication how much detail is required for the temporal disaggregation of daily precipitation totals. Such information indicates to which degree historical precipitation data or precipitation simulations from climate models – at daily resolution – might be sufficient to estimate flood peaks. While numerous patterns would be possible our simple approach covers the most extreme cases of concentration of all precipitation to one (or a few) hours or the even distribution over several hours. We tested our approach for nine mesoscale catchments in Switzerland with 35 years of hourly precipitation and runoff observations. We further looked at the flood mechanisms causing annual and seasonal peaks by categorizing them into flood-types using a recently developed fuzzy decision tree (Sikorska et al., 2015b).

Please note that this study focuses purely on the effect of precipitation daily totals evenly distributed into n hours on simulated runoff largest annual and seasonal peaks using observed data. An assessment of uncertainty in measured precipitation and runoff data (e.g., Di Baldassarre and Montanari, 2009; McMillan et al., 2012; Sikorska and Renard, 2017; Sikorska et al., 2018) or an estimation of the best precipitation disaggregation approach (e.g. Kossieris et al., 2018; Pui et al., 2012) both are a research focus on their own and are not considered in our approach to estimate the effective rainfall durations.

2. Material and methods

2.1. Study catchments and data

In this study, data from nine mesoscale Swiss catchments with the catchment area in the range of 40–500 km^2 were used (Table 1). Of the catchments, two were located in Northern Switzerland, two in Western Switzerland, three in Central Switzerland, and two in the Bernese Alps (Fig. 1) and have mean catchment altitudes between 511 m a.s.l. and 2050 m a.s.l. All of the three Alpine catchments have an area fraction of glaciers of more than 5%, which requires an adequate glacier melt routine in the hydrological model. Observation data for these nine catchments cover on average the period of 34.5 years of hourly records of precipitation and runoff at the catchment outlet. As observed precipitation data, we used information from hourly gauging stations which were then averaged to catchment mean precipitation totals using a Thiessen polygon method. Due to a relatively good coverage of gauging stations for the sample catchments, which in Switzerland is equal to 1.47 stations per 100 km^2 on average (Viviroli et al., 2011), we assume this interpolation approach to provide reasonable estimates of areal precipitation totals. Over the analyzed period, high flows in these catchments were not influenced by power plants or hydropower stations, nor by the presence of large lakes, which allows us to assume that observed runoff peaks are governed solely by precipitation, snowmelt and glacier melt dynamics. The extent

Table 1
Properties of our sample catchments sorted according to the increasing catchment mean altitude. The shaded rows indicate two study catchments chosen for presenting detailed results.

Catchment			Catchment properties				Runoff properties	
Topo-graphic region	Name	Id	Mean altitude [m.a.s.l.]	Area [km^2]	Areal glacier ratio [%]	Geo-graphic region[a]	Record length used	Regime type[b]
Swiss Plateau	Surb at Döttingen	C1	511	67	0	NS	1980-2015	pi
Swiss Plateau	Wigger at Zofingen	C2	660	368	0	NS	1980-2015	pi
Swiss Plateau	Mentue at Yvonand	C3	679	105	0	WS	1980-2015	pj
Average			617	180	0		35 years	
Pre-alpine	Kleine Emme at Littau	C4	1050	478	0	CS	1980-2015	nppa
Jura	Areuse at Boudry	C5	1060	377	0	WS	1983-2015	npj
Pre-alpine	Muota at Ingenbohl	C6	1360	316	0.1	CS	1980-2015	ndt
Average			1157	390	0		34 years	
Alpine	Grosstalbach at Isenthal	C7	1820	44	9.3	CS	1980-2015	na
Alpine	Kander at Hondrich	C8	1900	491	7.9	BA	1981-2015	ag
Alpine	Lütschine at Gsteig	C9	2050	379	17.4	BA	1980-2015	agn
Average			1923	305	11.5		34.7 years	
Average over all sample catchments			1232	292	3.9		34.5 years	

[a]NS – Northern Switzerland, WS – Western Switzerland, CS – Central Switzerland, BA – Bernese Alps.
[b]Defined according to Weingartner and Aschwanden (1992); pi – pluvial inférieur, pj –pluvial jurassien, nppa – nivo-pluvial préalpin, npj – nivo-pluvial jurassien, ndt – nival de transition, na – nival alpin, ag – a-glaciaire, agn – a-glacio-nival.

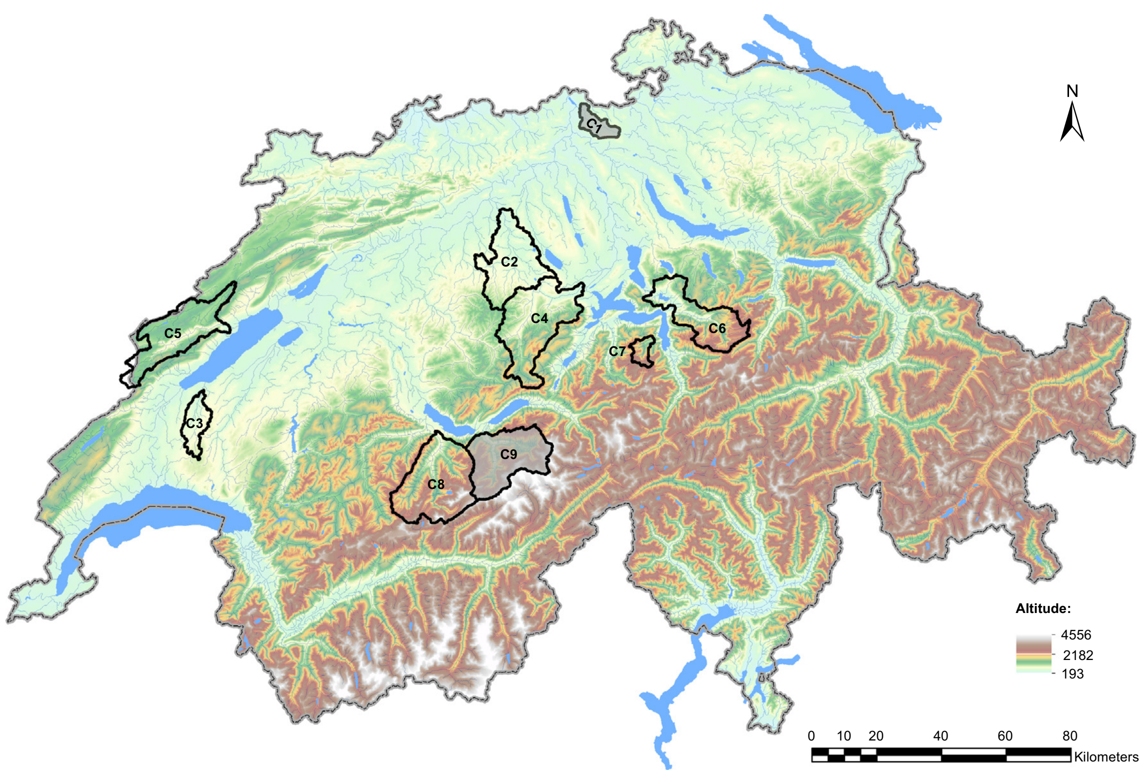

Fig. 1. Location of the nine sample catchments selected for the analysis. The two catchments with shaded area (see also Table 1) are chosen as study catchments for presenting detailed results.

to which these factors govern catchment hydrology in each catchment is to a large degree determined by the mean catchment altitude and described by the regime type. In this context, we differentiate between three groups of catchments according to the altitude zones proposed by Weingartner et al. (2003):

- Swiss Plateau (C1–C3) with the mean catchment altitude below 1000 m a.s.l.. Hydrological processes are expected to be mainly dominated by precipitation.
- Pre-Alps and Jura Mountains (C4–C6) with the mean catchment altitude between 1000 and 1500 m a.s.l.. Here, a mix of precipitation and snowmelt processes is predominant.
- Alps (C7–C9) with the mean catchment altitude above 1500 m a.s.l.. Snowpack and glaciers are expected to have a dominant control on runoff with limited precipitation contribution.

Because all of our sample mesoscale catchments have an area of at least several tens of square kilometres, runoff generation in these catchments is expected to be postponed in time, following the time of concentration concept (Grimaldi et al., 2012). We estimated this time of concentration with an approach common for flood estimation in Switzerland (Spreafico et al., 2003) as the maximum flow time in the catchment with assumed flow velocities of 1.5 m s^{-1} for the main channel and 0.5 m s^{-1} for all other areas (see also Viparelli, 1963 and Rickenmann, 1996). The resulting times of concentration correlate with the catchment area in our nine catchments and range from a minimum of 4 h (in the smallest catchment of Grosstalbach at Isenthal, C7) to a maximum of 12 h (in the largest pre-alpine catchment of Kleine Emme at Littau, C4). For a more in-depth and critical appraisal of estimating times of concentration, the reader is referred to Grimaldi et al. (2012).

2.2. Characteristics of the observed large precipitation events

As a direct approach to determine the average duration of large precipitation events, we examined characteristics of these precipitation events that were contributing to the annual runoff peaks. To this end, we analysed the precipitation intensity and the precipitation duration at the day of the annual flood episode and during three days preceding the flood episode. Specifically, we investigated over how many hours during a day different thresholds for the precipitation intensity were exceeded. Considered thresholds were 0.1 mm, 1 mm and 3 mm per hour. This exceedance length defines the precipitation duration during the analysed days. For consistency with runoff simulations that represent cumulative sums at the catchment outlet, we decided to define the daily precipitation as the sum from 0:00 until 23:59 (opposite to the definition based on the time of precipitation gauge readings such as 6:00–5:59). In this way, all precipitation falling within this window frame was attributed to the same day and as belonging to the same precipitation event.

2.3. Sub-daily precipitation distribution schemes

Next, observed hourly precipitation records were aggregated to daily totals (using a time window of one to 24 h; 01:00–24:00 h) and then evenly redistributed into *n* consecutive hours within each day (see Fig. 2), using values of 1, 2, 3, 6, 12 and 24 for *n*. The latter implies a constant precipitation during the entire day meaning that daily totals are uniformly distributed within 24 h. The first hour of precipitation was chosen randomly, but ensuring that the entire precipitation fell during the day in question. The random choice of the starting hour is important to avoid systematic errors in attributing daily precipitation totals always within the same time of the day, e.g. always in the night. Because the selection of the first hour was done for each observation day independently, the risk of choosing always the same hour within the 24-h days and the entire observation period could be minimized. Such generated different sub-daily precipitation time series were next used as inputs for a hydrological model to simulate runoff at the catchment outlet.

2.4. Hydrological modeling (HBV)

To simulate runoff at the catchment outlet, we used a conceptual bucket-type model, i.e., HBV in the version light developed at the University of Zurich (Seibert and Vis, 2012). This model has five major routines for modelling the precipitation excess, snowmelt processes, soil moisture and routing in the river, and in high altitude catchments also glacier melt, and thus is suitable for Swiss conditions. For more details on the HBV model, the reader is referred to Lindstrom et al. (1997), and on HBV light to Seibert and Vis (2012). The HBV model was run in this study at an hourly scale and (observed or generated) hourly precipitation time series and temperature observed data were used as inputs to simulate runoff continuously at an hourly time scale.

2.5. Model set up, calibration and uncertainty consideration

The HBV model was calibrated in nine sample catchments with 15 years of observed hourly runoff and precipitation data (years: 1990–2005). These optimized parameter sets were never changed after the calibration and were used for all model simulations with different sub-daily distribution schemes. To calibrate the model, we used a Genetic Algorithm and Powell optimization (GAP) approach (Seibert, 2000) within a multi-objective framework. Genetic algorithms (GAs) have been proved to be powerful and flexible tools in searching optimal solutions in water related research (Nicklow et al., 2010). The GA optimization relies on an evolutionary mechanism of selection and recombination of *x* parameter sets (parameter population) randomly selected within defined parameter boundaries. The value of each selected set is weighted using defined objective functions and only those sets that give the highest values of objective functions are retained. From these retained sets, a new parameter population (sets) is generated and this process is repeated until the given maximal value of permitted model runs is reached. Next, the best obtained parameter set is used as a starting point for a local optimization search using the Powell's quadratically convergent method (Press et al., 2002). In this study, the total number of model runs was set to 3000, with 2500 runs for the GA and 500 runs for the local Powell's optimization.

In the multi-objective framework three objective functions were used: the Kling-Gupta Efficiency (KGE), the Peaks' Efficiency (PE) and the Logarithmic Efficiency of runoff (LE) (Gupta et al., 2009; Seibert, 2003; Vis et al., 2015), which were weighted as 0.3, 0.5 and 0.2, respectively. Each of these objective functions is defined in a similar way as the Nash–Sutcliffe efficiency, i.e. they values vary from 1 to $-\infty$, where 1 represents the perfect fit between the simulated and the observed variable. The same applies to the weighted efficiency (WE) which is the weighted mean of the different objective functions. The efficiency metrics and their weights were assigned in pre-analysis aimed at maximizing the model WE and its fit for peaks. The achieved average WE in all nine sample catchments in the calibration period was equal to 0.72, with an average KGE equal to 0.79, LE to 0.68 and PE equal to 0.70. In the period of the model application (i.e., years: 1980–2015), the WE was on average equal to 0.62, KGE to 0.77, LE to 0.70, and PE to 0.5. As an approach to consider parameter uncertainties, the model calibration in each catchment was repeated 100 times giving 100 model parameter sets for runoff simulations. Using these 100 model parameter sets, continuous hourly runoff series for the period of 1980–2015 were simulated using six different sub-daily precipitation distribution schemes.

2.6. Selection of annual and seasonal peaks from continuous runoff time series

The HBV model simulates continuous runoff time series at an hourly scale, from which annual and seasonal peaks need to be filtered. These peaks were extracted following the common annual maxima series (AMS) procedure and in a similar way for seasonal peaks – seasonal maximum series (SMS) approach. For this purpose, we defined four seasons within the calendar year as: winter (I–III), spring (IV–VI), summer (VII–IX) and fall (X–XII). For consistency between different simulation schemes, the selection of annual and seasonal peaks was based on the runoff series simulated with the observed hourly precipitation (Pobs) which was treated as the benchmark, whereas peaks simulated with six sub-daily distributed precipitations (P1h–P24h) were selected as maximal peaks belonging to the same flood episodes. To this end, a

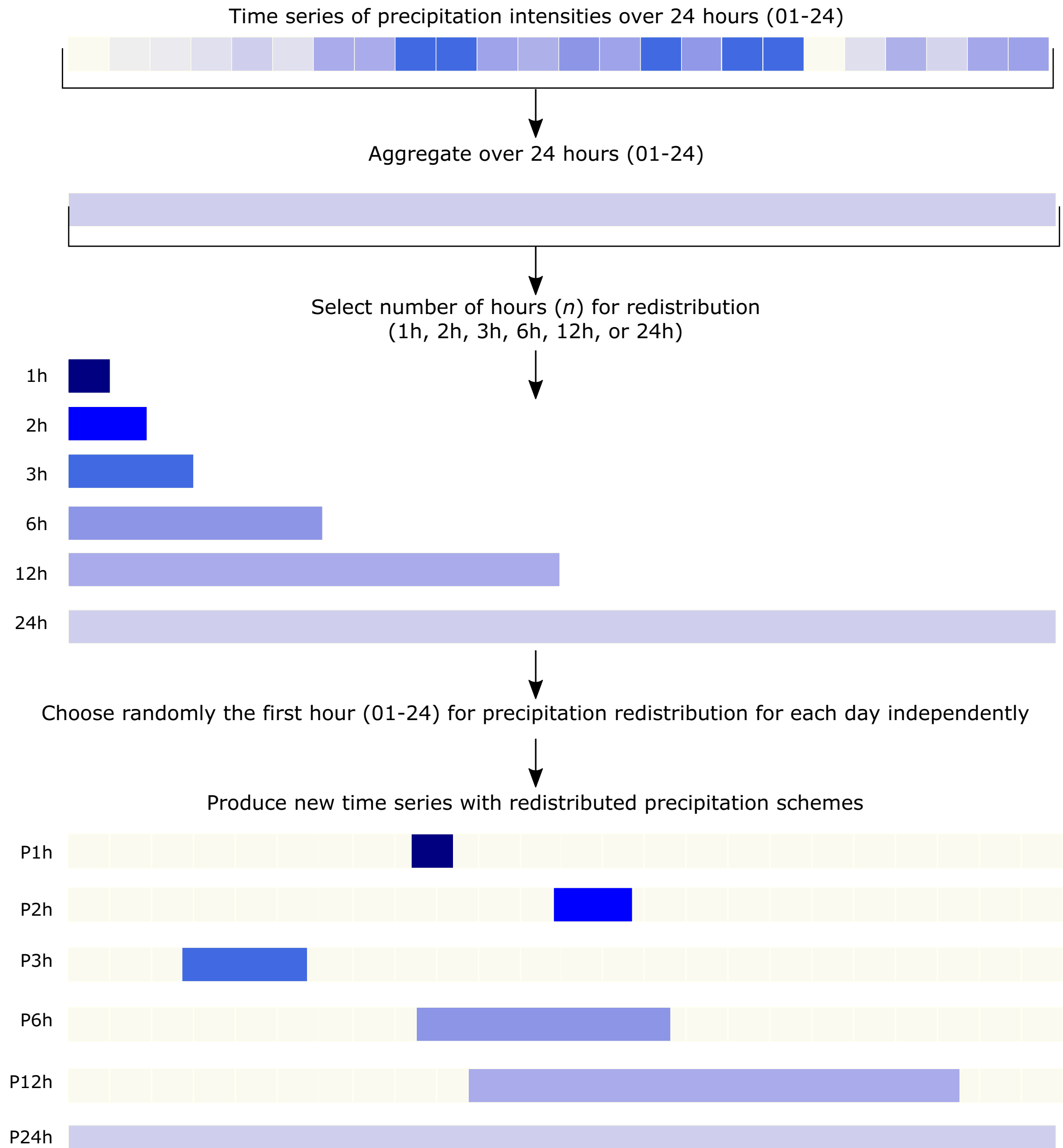

Fig. 2. Overview of aggregation and redistribution of daily precipitation sums into sub-daily schemes.

window with a total duration of 6 days (i.e., interval of 72 h before and after the maximum observed peak at an hourly time scale) was set around the selected peaks simulated with benchmark precipitation. Within this window the highest flows (i.e. peaks) were searched for. Note that in the extreme case, when the flood episode simulated with the benchmark occurs at the very end or beginning of the season (year), the peaks with simulated sub-daily distribution schemes might be chosen in the following or preceding season (year).

2.7. Assessment of simulated peaks: The effective daily precipitation duration

We further define *the effective daily precipitation duration* which corresponds to the catchment time of concentration with the difference that is determined from peak simulations of a hydrological model only. This effective daily precipitation duration is described as a number of n hours for which the simulated runoff peaks with different sub-daily precipitation distributions are closest to those being simulated with the hydrological model using the original hourly precipitation time series (benchmark). Thus, we always assess how much worse it is compared to using original precipitation hourly data distributed precipitation time series as input to the model. We introduce here the term *relative peak* which is obtained by simply dividing a simulated peak by the benchmark peak. Hence, if the relative peak equals unity, the perfect agreement between the benchmark and simulated peak is obtained. If the value of a relative peak is higher than 1, the peak is overestimated, and if it falls below 1, it is underestimated.

The assessment of simulated peaks was further analysed by fitting empirical probability density functions (pdfs) to relative annual and seasonal peaks independently for each of six sub-daily distribution schemes. The sample size for constructing such pdfs depended on the record length in each catchment and consisted of roughly 34.5 (annual or seasonal) peaks on average. Such fitted pdfs provide additional insights into the efficiency in simulating peaks with different sub-daily distribution schemes. Each fitted pdf can be expressed with the mode (the most common value) and the span of the pdf around this mode. As for simulated relative peaks, the second information is especially important because modes of different pdfs may lie at or close to the desired unity line, but their span may vary (representing the sample variability). Hence, we are searching here for the pdf with the smallest span and the mode as close to unity as possible. As mentioned above we used 100 different calibrated parameter sets to consider parameter uncertainty, which means that 100 runoff time series were simulated and 100 simulated peak values were generated for each of six sub-daily distribution schemes.

3. Results

In the following, detailed results are presented for two study catchments, the lowest (Surb-Döttingen, C1) and the highest (Lütschine-Gsteig, C9). The results for these catchments can be assumed representative for all nine catchments, as seen from the summarizing results presented for all nine sample catchments.

3.1. Characteristics of precipitation events preceding annual runoff peaks

The analysis of precipitation characteristics during the largest peaks indicated that the duration of precipitation events depended on how we defined the intensity threshold for defining an hour as having precipitation. For the smallest threshold considered ($P \geqslant 0.1$ mm h^{-1}), the average precipitation event in most catchments lasted for several hours (between 10 and 16) on the day the flood episode occurred and on the day directly preceding the flood event (see Fig. 3 for example catchments). Increasing the intensity threshold ($P \geqslant 1$ mm h^{-1}) resulted in shortening the average duration of the precipitation event, to about 5–8 h on the day of the flood event and the day directly before. Finally, setting the threshold at $P \geqslant 3$ mm h^{-1} resulted in further shortening the average precipitation event duration, which lasted less than 4 h on the day of the flood event and the day before.

Precipitation characteristics in all nine sample catchments over 35 years demonstrated that most of the precipitation events which led to annual peaks in these catchments were long-lasting (several hours over at least two days) and of a low hourly intensity ($P < 1$ mm h^{-1}). Furthermore, similar to the findings for C1 and C9 catchments, the definition of the threshold largely influenced the computed precipitation duration in all nine catchments. On average, the precipitation duration during the day of the flood event was 13 h when a threshold of 0.1 mm h^{-1} was used whereas it was 3 h for a threshold of 3 mm h^{-1}.

3.2. Results from sensitivity analysis to the sub-daily precipitation distribution

3.2.1. Simulated annual peaks for the six precipitation distributions

The relative annual peaks simulated with 100 different parameter sets showed that distributing the daily precipitation over only 1–3 h led to overestimated peaks in both C1 and C9 catchments (Fig. 4) and this was also the case in most other sample catchments. Contrarily, the precipitation distribution over 24 h resulted in underestimated peaks. It appears therefore that the sub-daily distribution over 6 and 12 h resulted in the best simulated peaks for all nine sample catchments (the boxplots lie closest to the intersect line 1).

The results for C1 and C9 generally also apply to the other catchments (Fig. 5). The simulated peaks were closest to a mean of one when the daily precipitation was distributed over 12 h whereas shorter periods lead to overestimated peaks, and the distribution over the entire day to an underestimation.

Fig. 6 further summarizes the results. In the smaller catchments (C7, C1 & C3), different precipitation distribution schemes generally lead to considerable changes in the relative annual peaks, ranging from marked underestimation to equally marked overestimation. This is valid both for small catchments located on the Swiss Plateau (C1 & C3) and to a lower extent for the small Alpine catchment (C7) in our sample. Similar patterns were observed for two medium catchments (C6 & C2). The largest Alpine catchments (C8 & C9), in turn, were generally less sensitive to the choice of the distribution scheme. In contrast, the largest pre-alpine catchment (C4) was very sensitive to changes in the distribution. The only Jura catchment (C5) appears to be insensitive to the choice of the hour distribution.

3.2.2. Simulated seasonal peaks for the six precipitation distributions

The simulated seasonal peaks indicated that using distribution schemes of 1–3 h led to a marked overestimation of spring and winter peaks and a modest overestimation of summer and fall peaks in the catchment C1 (Swiss Plateau). A 24-h scheme always underestimated peaks independent of the season. The peaks were simulated the best when using the 12-h distribution scheme (Fig. 7). In the second catchment C9 (Alpine), the degree of a sub-daily distribution did not play any role for spring and winter peaks because all schemes provided a similarly good fit, but it did play a role for fall and summer peaks, for which the best estimation was observed for the 6 and then the 12-h precipitation distribution scheme.

Analyzing detailed results in all nine sample catchments revealed similar patterns (not shown) to those already observed for annual peaks, i.e., a 12-h distribution scheme simulated at best seasonal peaks for most catchments and this effect was observed to be independent of the season. Yet, in the highest-elevation Alpine catchments (C7–C9), the 6-h scheme was found to be a better choice for spring and summer peaks than a 12-h scheme but had wider confidence intervals.

4. Discussion

4.1. Patterns in simulating annual and seasonal peaks with different precipitation sub-daily distributions

The effective daily precipitation duration was about 12 h in all catchments independent of the catchment size and the season. This finding was demonstrated by the fact that a 12-h sub-daily precipitation distribution scheme best simulated both annual and seasonal peaks. A 6-h scheme was the second best choice, and in Alpine catchments it provided as good results as the 12-h scheme for spring and summer floods.

Looking at the sample catchments examined, a clear relation would be expected between the catchment area on the one hand and the best sub-daily distribution on the other hand: Following Mulvaney (1851) and his idealized assumptions for the Rational Method, the major floods in a catchment are produced when the entire area contributes to runoff. This state can be characterized by the time of concentration and is generally reached more quickly in smaller catchments. Since the maximum possible precipitation intensity increases when the event duration decreases, this means that smaller catchments are particularly reactive to short but intensive precipitation events in producing their highest peaks. In our analysis, this pattern holds only to a limited extent. This is

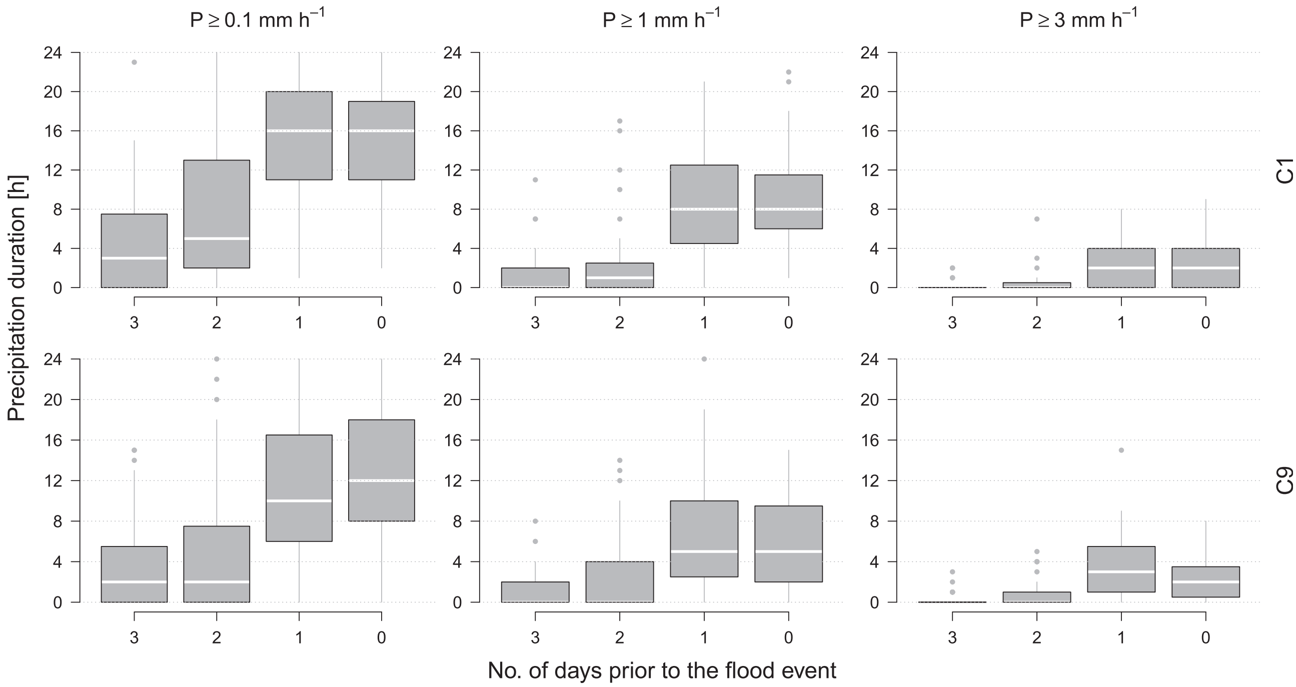

Fig. 3. Precipitation duration in hours during the day of the annual maximal flood event and the three days preceding these flood events for three different precipitation thresholds in the two study catchments: Surb-Döttingen (C1) and Lütschine-Gsteig (C9).

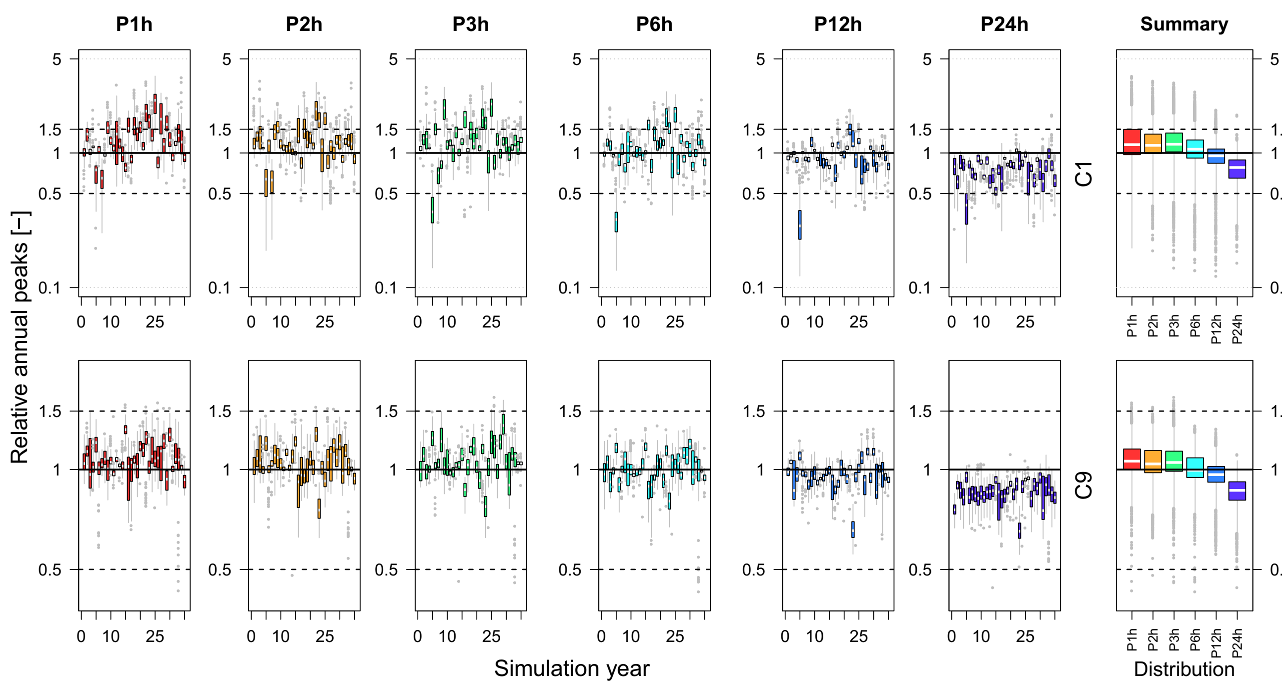

Fig. 4. Effect of precipitation sub-daily distribution on simulated annual peaks using 100 best HBV parameter sets over 35 simulation years for two study catchments: Surb-Döttingen (C1) and Lütschine-Gsteig (C9). The solid horizontal line 1 depicts the case when annual peaks simulated with distributed sub-daily precipitations equal peaks simulated with observed hourly precipitation. Thus, the farther from this line the boxplots lie, the worse peaks with sub-daily distributed precipitation are simulated, where shifting boxplots upwards means overestimation and shifting downwards – underestimation of annual peaks. Note that the y-axis is a logarithmic scale.

because one needs additionally to consider several effects confounding the relation between the catchment area and the best distribution scheme.

First, the concept of the time of concentration and the maximum contributing area refers to rainfall-driven events only and is based on the concept of maximum possible peaks. In contrast, in our study we examine a series of annual and seasonal peaks observed in the past which to a large extent encompass events of a mixed genesis (see Section 4.5). The precipitation input thus provides only one contribution to the flood peak, while the other contribution (sometimes major) comes from melt processes. This explains why the differences between the various precipitation distribution schemes are comparatively small for large Alpine catchments. The significant contributions of snowmelt and, to a

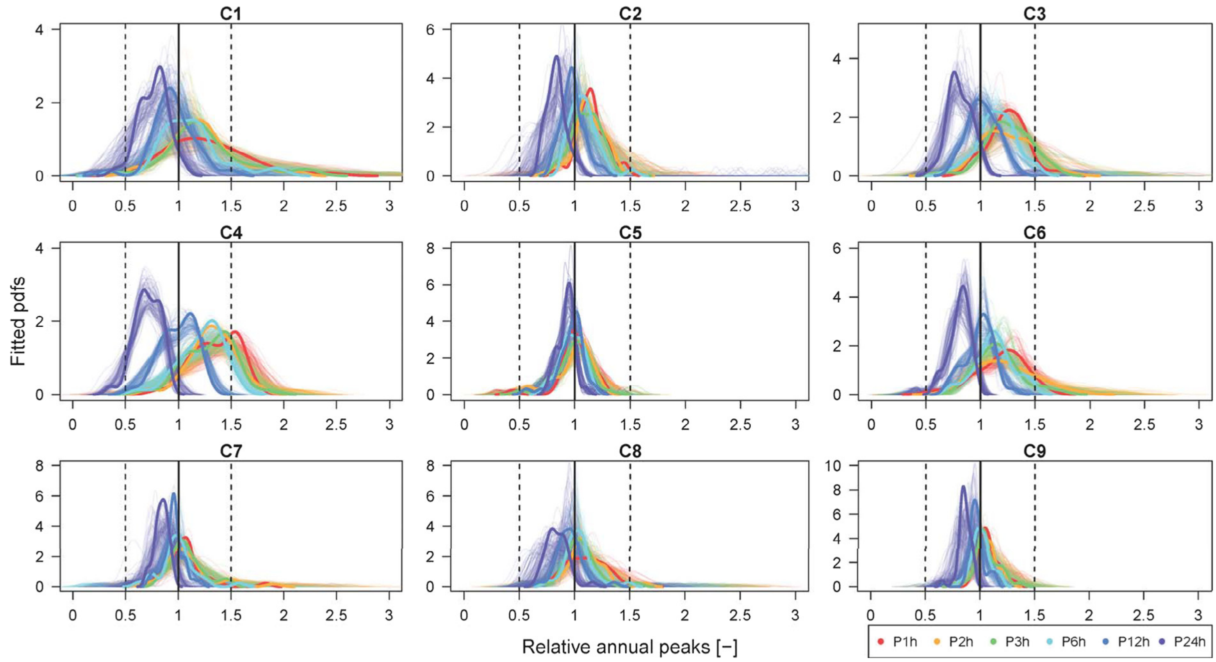

Fig. 5. Empirical density functions fitted to simulated relative annual peaks over all simulation years with different sub-daily precipitation distribution schemes (P1h-P24h, the number reflects a number of hours over which the distribution was evaluated). The semi-transparent envelopes depict pdfs fitted to peaks simulated with 100 different parameter sets, while solid envelopes represent the ensemble mean over all 100 parameter sets. The narrower and the closer centred on the vertical line 1 the mean envelope lies, the better the fit between peaks simulated with sub-daily distribution and those with observed hourly precipitation (benchmark).

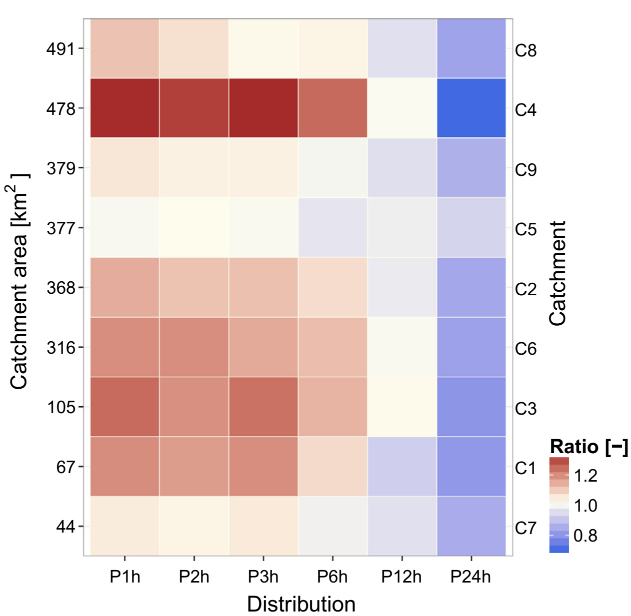

Fig. 6. Association between the accuracy of simulating annual peaks with different sub-daily precipitation distribution schemes (1–24 h) and the catchment area. Catchments are sorted by increasing area (smallest: C7, largest: C8). Medians of annual peaks are displayed as relative values in accordance to the peaks simulated with observed hourly precipitation data: the ratio indicates whether peaks are overestimated (>1) or underestimated (<1).

smaller extent, glacier melt call for consideration of distinctive hydrological processes leading to large floods that can be represented with specific flood-types (Section 4.5). Second, small catchments may indeed be receptive for short and intense precipitation events. When the causative precipitation event is not an isolated one but rather embedded in a longer-lasting frontal event, compressing the daily precipitation total into a few hours only may lead to unrealistically high precipitation input for the catchment and the hydrological model. The result would be an overestimation of flood peaks for the sub-daily distribution that corresponds to the time of concentration, as also observed in our case for the smallest catchments. Finally, it is also worth noting that all of our catchments are at least of roughly 40 km^2 and thus fell rather into a medium/large size catchment group, in which large floods are rather due to precipitation events of several hours or intense snowmelt/rain-on-snow events (Merz and Bloschl, 2003). This could be explained with an extended time of concentration in such larger catchments. Thus, in catchments smaller than analysed here (<40 km^2) a more detailed sub-daily precipitation distribution scheme could still be expected to be important. Similarly, in catchments larger than those investigated here, or having a slower response time, a disaggregation of daily totals into sub-daily sums may not be needed.

4.2. Usefulness of the effective daily precipitation duration concept

A direct analysis of precipitation event durations of the largest floods partly confirmed our findings from this simulation study but, as expected, additionally highlighted problems with defining the precipitation event duration based only on precipitation data. Thus, depending on how we set the threshold for defining the precipitation occurrence, very different results can be obtained. This further shows that such arbitrary choices may indeed impact results and conclusions drawn from them. In contrast, our approach provides an alternative way of determining the effective daily precipitation duration from runoff simulations only. Hence it avoids making such arbitrary decisions related to the precipitation duration and the minimal precipitation intensity, as it purely examines the effect of different precipitation distributions on simulated runoff peaks. Thus, it is more efficient from a hydrological point of view.

Focusing solely on the effect in simulating peaks with a hydrological model instead of precipitation also ensures our method to

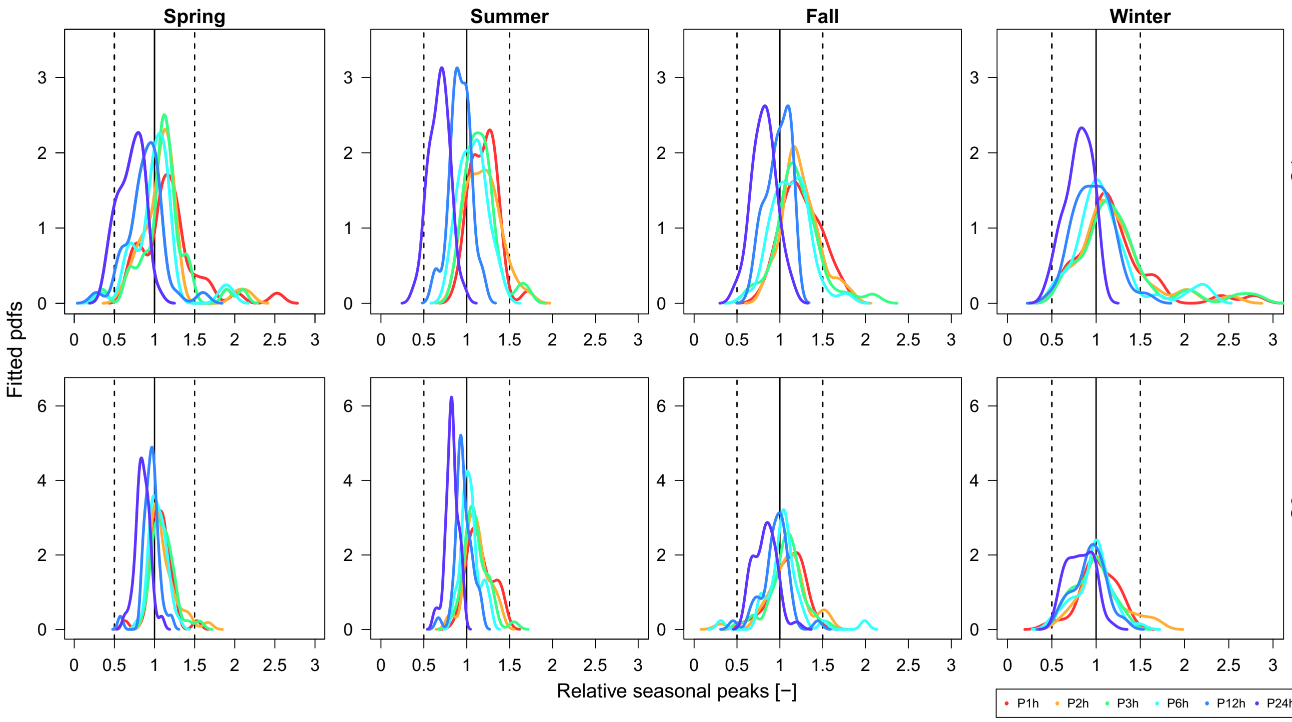

Fig. 7. Density functions fitted to simulated relative seasonal peaks over all observation years with different sub-daily precipitation distribution schemes (P1h–P24h) using the best HBV parameter set for the two study catchments Surb-Döttingen (C1) and Lütschine-Gsteig (C9). If a peak matches perfectly, the corresponding envelope should lie exactly on the 1 vertical line. For the sake of simplicity, we present only the ensemble mean pdfs.

be independent from the type of the flood event considered. Thus it is suitable for any type of flood and also for those types that are not driven by precipitation events such as related to snow/glacier melt processes. This is one of the major advantages over the direct analysis of precipitation information which is thus limited to precipitation-driven events only. Hence, our approach may provide a feasible alternative to more advanced statistical approaches despite the fact that the detailed information on precipitation intensity variability becomes lost during aggregating and redistributing precipitation totals. It has to be noted however that one reason for this might be the finding of the effective daily precipitation duration of about 12 h, meaning that the exact precipitation intensity within a shorter period was, in our case, not so important.

These findings support the use of such a simple precipitation distribution approach which has several practical applications; It complements more current records available at hourly resolutions with past records disaggregated to sub-daily sums allowing for more detailed retrospective analysis of past floods; Together with runoff data, that is usually available at sub-daily time steps from longer periods, it supports continuous hydrological modelling at hourly resolutions (Kossieris et al., 2018); It extends the pool of observed flood events for statistical reasoning of extremes, for which a large data sample is required (Reed, 2002), but also for investigating flood processes. Finally, it allows making usage of precipitation simulations from climate models that are currently available at a daily scale to investigate impacts on flow dynamics and flood magnitudes.

4.3. Robustness of results and uncertainties

There are several potential sources of uncertainty in this work which might affect estimation of annual and seasonal peaks. First of all, both observational data, i.e., precipitation and runoff are subject to measurement and representation uncertainty (mostly precipitation) which cannot be completely neglected but are difficult to quantify as the true values are not known (e.g., Di Baldassarre and Montanari, 2009; McMillan et al., 2012; Sikorska and Renard, 2017; Sikorska et al., 2018). To minimize this type of error, both runoff and precipitation data were checked for inconsistency or systematic errors prior to the analysis by visual assessment and analysis of water balance components. Next, the runoff simulations are uncertain due to the structural limitations of the hydrological model HBV, its parametric uncertainty, and boundary conditions as due to choices of initial values for state variables (Kuczera et al., 2010; Sikorska et al., 2012). The latter source can be minimized by setting up a warm-up period prior to the simulation and Seibert and Vis (2012) have revealed that one year of such a warm-up period is sufficient for this kind of model and thus was also used in this study. The structural uncertainty is linked to the structure of the hydrological model used in this study and affects estimation of all other uncertainty sources including model parameters (Sikorska et al., 2015a). This structural uncertainty source cannot be avoided in any environmental conceptual model but because the same model was always used with the same settings (initial conditions, model structure type, model parameters) for all sub-daily precipitation distribution schemes, this allowed us to assume that this uncertainty contribution was always the same and thus did not affect our results. Finally, the parametric uncertainty was considered by using multiple (100) parameter sets for model simulations. This should minimize the effect of the parameter uncertainty on the obtained results and demonstrated how strong results depend on the choice of the parameter set chosen for the hydrological model. As our findings manifested, the conclusions did not depend on the choice of the parameter set because flood peaks with different sub-daily precipitation distribution schemes were always over- or underestimated by the same magnitude.

4.4. Methodological aspects and study limitations

Our analysis is based on sampling peaks according to the annual maximum (AM) and seasonal maximum (SM) approach. By compounding our analysis with seasonal peaks, we demonstrated that our findings hold not only for large annual but also for more frequent (and thus smaller) peaks, i.e. in total 4 peaks per annum are selected. The choice of AM and SM approaches was in our case favorable to investigate seasonal flood events and to cover the flood variability resulting from different flood types. Optionally, peaks could also have been chosen with a peak over threshold (POT) approach which selects peaks not on the maximum per period criterion but based on a preselected threshold flow value. Although the POT approach is often preferred, both POT and AM approaches have been proven to provide similar results in case of long time series (Tanaka and Takara, 2002). Thus, using the POT approach with a low threshold would result in selecting peaks of magnitudes similar to those chosen with the SM approach and thus would not change our major findings.

Our method relies on evenly distributing precipitation daily totals into sub-daily sums of constant precipitation intensities. If a diversification of precipitation intensities at sub-daily intervals is required, one could use certain patterns such as a triangular shape instead of the uniform distribution. An optimal distribution function could also be investigated from observed data. Furthermore, the method is based on a random selection of the first hour for different sub-daily precipitation distribution schemes. Although the choice of this hour plays potentially an important role for model simulations, as we always randomly selected this hour for each simulation day independently over roughly 35 years of simulations, this effect could have been minimized.

Another discussion point is linked to the way the hydrological model is used in this study, namely that it was pre-calibrated with hourly observations of precipitation and runoff data. The effect of the sub-daily precipitation distribution on simulated peaks was then assessed on the basis of this model, keeping model parameters constant. This means two things; First, for calibrating the model at least some short series of hourly precipitation-runoff data are required. In this respect, Sikorska et al. (2018) have proposed a suitable method for assessing the minimum length of the calibration period needed to obtain a sensible model performance. In the case that no calibration data are available, this restriction could be alleviated by deriving model parameters from regionalisation approaches (Parajka et al., 2013), a limited number of runoff measurements (Seibert and Beven, 2009) or a combination of both (Viviroli and Seibert, 2015), but would add additional uncertainty to results. Second, calibration on precipitation and runoff data with an interval of more than one hour could lead to a different model performance when using the corresponding distribution of daily precipitation totals for simulation. Our study did not examine this effect as we explicitly focused on hourly values as a starting point.

Finally, our simulations were assessed with the HBV model which is a typical bucket-type model with several hydrological processes being represented in a conceptual manner. As important for our study, such a model uses lumped inputs computed as mean areal precipitation totals and thus the spatial representation of precipitation events does not play any significant role. The temporal distribution of precipitation still remains important but is represented with lumped values at the catchment scale only. Thus, for other type of models (distributed) with a more detailed spatial description of precipitation inputs a different distribution extent of precipitation totals may be required, which can be assessed with the method proposed in this study. Yet, in our opinion, the necessary extent of precipitation distribution depends largely on the delay in the catchment reaction relative to the triggering input and only to a lower extent on the model type chosen for simulating floods, as long as peaks of large floods are considered like in this study.

Following the last point, it has to be stressed that our study focuses only on the effect which evenly distributing daily precipitation totals into sub-daily sums has on the peaks of large floods, whereas the effect on the evolution of flood events is here not considered. We expect that a more detailed representation of precipitation distributions within a day will play a role if other characteristics of flood events or the entire flood hydrographs are of one's interest. Indeed, these aspects have been recently quantified by Sikorska and Seibert (2017) who tested different options of averaging observed hourly precipitation time series for an acceptable model performance focusing on entire hydrographs. In their study, they found that the sufficient length of precipitation averaging window varied from 1 to 24 h depending on the catchment size and the source of precipitation records. Our findings on the effective daily precipitation duration equal to half a day falls in the middle of this range, which is reasonable given the size of our sample catchments.

Despite these limitations, results of our study proved that this approach is suitable for identifying an optimal (effective) temporal length for sub-daily precipitation distribution in mesoscale catchments and thus it can be used as a hydrological alternative to a direct analysis of precipitation data. Therewith it enables making a usage of daily precipitation data for flood simulations and particularly for analysis of flood peaks at an hourly resolution.

4.5. Hydrological reasoning: Flood-types of annual and seasonal floods

The simulation study presented above purely examined magnitude changes in flood peaks with only a limited process understanding expressed with the flood seasonality (episode occurrence within a year) but without looking at flood drivers, thus treating all floods as one group. The major challenge of pooling all floods together is the non-possibility to distinguish between different processes driving floods which may potentially play a role in defining the effective daily precipitation duration. For instance, this value would be rather smaller for flash floods driven by short intensive precipitation events than for slowly rising floods due to melt processes.

In this respect, the recently developed fuzzy flood-type decision tree Sikorska et al. (2015b) enables hydrological reasoning to be incorporated into peaks analysis by diagnosing flood causative mechanisms responsible for observed episodes. Therewith the tree allows the splitting of the flood sample into sub-groups of specific flood-types according to their observed properties using similarity metrics (flood indices). The splitting into sub-groups is performed by attributing fuzzy memberships (m_f) defined from 0 to 1. The m_f equal 0 means that a certain flood-type did not occur (probability equals 0), and 1 that this type occurred with certainty (probability equals 1), while memberships in the range from 0 to 1 are attributed depending on how strongly the event belongs to a certain flood-type (see Sikorska et al. (2015b) for more details). Note that the flood tree does not allow an exact value of the effective daily precipitation duration to be identified, as it was possible with our simulation study, but only pre-defined classes of events, i.e., flood-types. Following Sikorska et al. (2015b), we considered here six distinctive flood-types which are: flash floods (FF), short rainfall floods (SRF), long rainfall floods (LRF), rain-on-snow events (RoSF), snowmelt events (SMF) and glacier melt floods (GMF). As for this study, the important information contained in these flood-types is the duration of the precipitation event and its intensity and both of these characteristics vary by definition between the six types considered here. Namely, FFs are defined by very short (<12 h) and intensive rainfall events and are implicitly spatially limited to smaller catchments (in this study with an area $\leqslant$120 km^2). SRFs correspond to short rainfall events with a precipitation duration of 12–24 h and an average precipitation intensity. LRFs and RoSFs are both long lasting events ($\geqslant$24 h) with the precipitation of low intensity, with the difference that RoSF occurs as a rainfall event on snow cover accumulated in the catchment, whereas LRF is generated without any significant contribution from snow cover. SMFs and GMFs are both driven by melted water originating from snowpack (SMF) or glacier (GMF) with an insignificant contribution from rainfall, and can only occur if a snowpack or glacier are present in the catchment prior to the event.

Application of the fuzzy decision tree in our sample catchments revealed that, among annual floods, SRF and RoSF were detected as dominant flood-types in Plateau catchments (C1–C3) with average memberships (m_f) of 0.55 and 0.32, and in Pre-alpine and Jura catchments (C4–C6; m_f equal to 0.56 and 0.41). In Alpine catchments (C7–C8), SRFs (0.33), RoSFs (0.31), glacier melt floods, GMFs, (0.17) and in the smallest Alpine catchment (C7) FFs (0.20) were also determined as dominant flood-types of annual peaks. Considering seasonal flood-types, seasonal floods in Plateau ($m_f = 0.61$), and in Jura and Pre-alpine catchments (0.52) were distinctly dominated by SRF, mostly responsible for spring, summer and fall peaks. The second major contribution was due to RoSF events (0.20 and 0.43 respectively), which contributed mostly to winter peaks. Seasonal floods in Alpine catchments (C7–C9) were identified mostly due to RoSF events with a contribution of 0.51 on average and were mostly detected in winter and fall. SRF events were the second major contribution (0.30) and were detected in spring, summer and fall seasons. Other contributions were due to flash floods (FF, 0.09 only in C7 and in summer and spring) and glacier melt floods (GMF, 0.07) in spring and summer (Fig. 8).

These observations on annual and seasonal flood-types found that large annual and seasonal floods a) were mostly driven by events of a mixed genesis, and b) mostly induced by precipitation events lasting at least several hours but shorter than a day, for which an exact precipitation distribution is of low importance. Hence, these results of the flood-type categorization are consistent with our findings from this simulation study suggesting that the effective daily precipitation duration for annual and seasonal floods can be assumed as 12 h. Thus, an even distribution of precipitation daily totals over several hours rather than only a few hours is most suitable. Yet, when looking only on flood magnitudes (peaks) within the simulation study, even with information of their seasonality, it would not have provided enough information to draw sensible conclusions because it leaves room for misinterpretation. Using a flood-type tree enabled us thus to better understand our simulation results.

Already several recent studies have pointed out that flood analysis should incorporate process understanding (Brunner et al., 2017; Merz and Bloschl, 2008; Sauquet and Catalogne, 2011). For example, Brunner et al. (2017) have demonstrated that information on specific flood-types can support flood frequency analysis with additional information on flood behaviour and seasonality. This information may be particularly useful in flood predictions and flood-risk management and allows for more dedicated flood prevention designed to a specific flood-type event. Merz and Bloschl (2008) proposed a "flood frequency hydrology", which incorporates hydrological processes into statistical frequency analysis, as a needed step towards improving designed flood predictions. Our results also demonstrate the suitability of such a dedicated flood tree approach to qualitatively analyse results of hydrological simulations and to diagnose observed floods, and in this way to support results obtained with formal methods with hydrological reasoning.

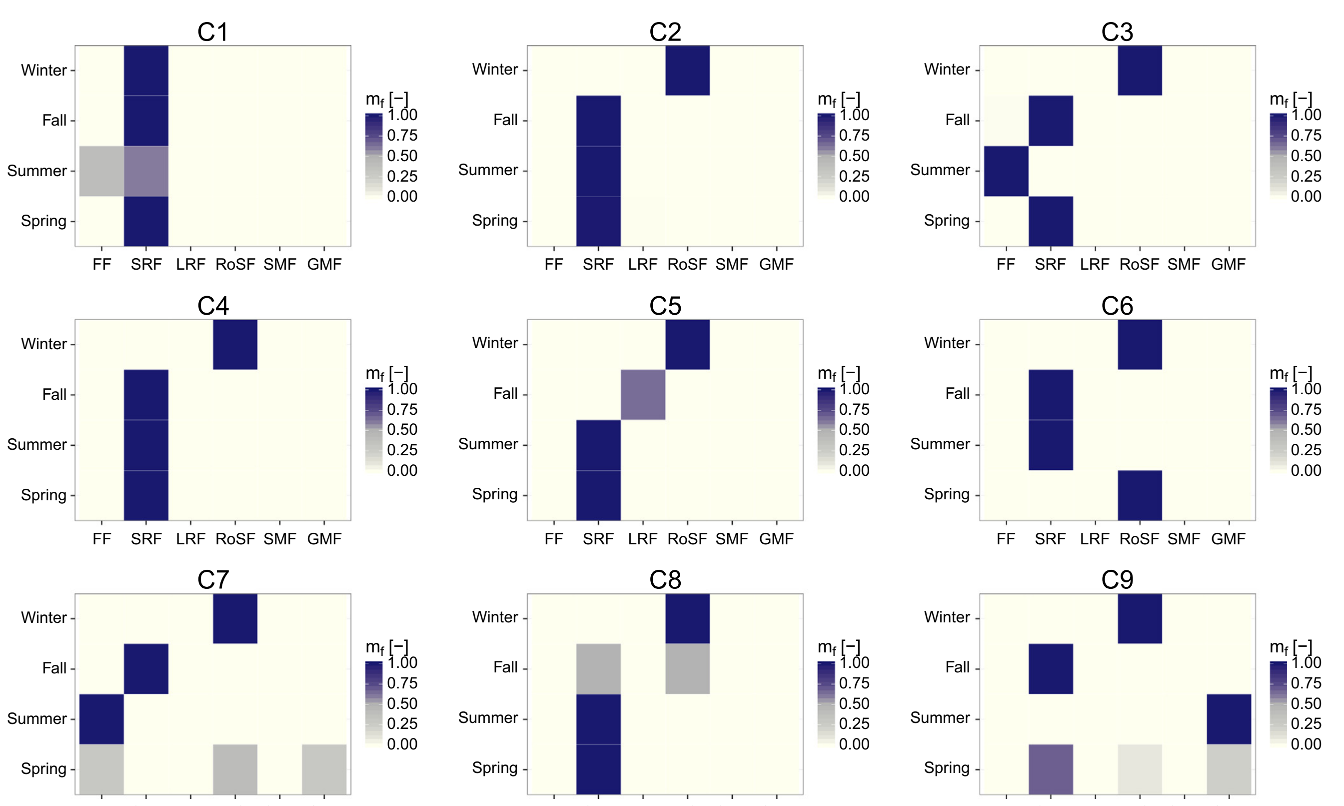

Fig. 8. Flood-type categories represented as fuzzy memberships (m_f) identified for seasonal floods using the fuzzy decision tree. Flood-type categories: FF – flash floods, SRF – short rainfall floods, LRF – long rainfall floods, RoSF – rainfall-on-snow floods, SMF – snowmelt floods, and GMF – glacier melt floods. Catchments are sorted by increasing mean altitude (lowest: C1, highest: C9).

5. Conclusions

The results of this study allow us to draw the following conclusions:

- The duration of precipitation events leading to annual flood peaks depends strongly on how we define the threshold precipitation intensity for the event. In our case, most of the observed precipitation events lasted over about 13 h on the day of the flood event and the day before when assuming the threshold of 0.1 mm h^{-1}, but only 3 h if the threshold was increased to 3 mm h^{-1}.
- The best choice for simulating annual and seasonal peaks in the studied catchments was a sub-daily precipitation distribution scheme over 12 h assessed by relative peaks. Sub-daily distributions over 1–3 h always overestimated peaks, while a 24 h scheme always slightly underestimated peaks. A 6 h scheme usually overestimated peaks in Plateau, Jura and Pre-alpine catchments, but was the second best choice for Alpine catchments.
- Results from our study indicate that the exact distribution of precipitation during a day might be less important and simple disaggregation schemes like the uniform distribution might be sufficient for simulating largest flood peaks in catchments similar to investigated here. While short time precipitation variations are still expected to be important for small catchments, for catchments above 40 km^2 the effective daily precipitation duration was in the order of 12 h. For catchments larger than 500 km^2, or slow reacting catchments, we expect that a sub-daily distribution would not be needed.
- Our simulation findings are consistent with flood processes driving observed large floods. Most of the annual and seasonal flood events were identified as mixed genesis and either with a major contribution of precipitation events of at least 12 h with medium to low precipitation intensities, or due to rain-on-snow events, for which an exact sub-daily precipitation distribution within a day becomes irrelevant.
- Finally, we present here a novel method to evaluate the effective daily precipitation duration from hydrological simulations, which is useful to characterise precipitation characteristics for different catchments and different geographic regions and for their inter-comparison without the need to analyze precipitation data. Our method, as an inverse approach, allows for estimating the degree of sub-daily precipitation disaggregation needed which is useful for extending hourly records or making usage of daily precipitation totals such as from climate model simulations available currently at daily resolutions.

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