

## Regional flood risk—what are the driving processes?

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**Abstract** In this paper a framework for identifying types of causative mechanisms of floods is proposed. The types are long-rain floods, short-rain floods, flash floods, rain-on-snow floods and snowmelt floods. A catchment perspective is adopted, i.e. the focus is on the catchment state and the atmospheric inputs rather than on atmospheric circulation patterns. A number of process indicators, including the timing of the floods, storm duration, rainfall depth, snowmelt, catchment state, runoff response dynamics and spatial coherence, are presented. Based on a combination of these indicators and diagnostic regional plots, the process types of 11 518 maximum annual flood peaks in 490 Austrian catchments are identified. Of the flood peaks, 43% are long-rain floods, and only 3% are snowmelt floods, and the relative contribution of the types changes with the flood magnitude. All process types exhibit pronounced seasonal patterns. The flood types analysis provides useful information for flood frequency regionalisation.

**Key words** Austria; flood processes; flood process typology

### INTRODUCTION

The physical processes giving rise to floods of a given probability of occurrence are controlled by a range of variables, including rainfall regime, snowmelt, state of the catchment and catchment characteristics. Because of this complexity, analysing and estimating flood probabilities is usually based on fitting a statistical distribution (the flood frequency curve) to a sample of observed flood peaks or regionalized flood information. However, statistical distribution functions only represent the cumulative effect of all the flood producing processes and their interaction in a global way, and do not provide any insight into the physical causes of the floods. Because of the lack of a physical basis, it is likely that the statistical distribution approach tends to perform poorly when one tries to extrapolate flood probabilities beyond the conditions of the sample. What is therefore needed is an approach that involves more understanding of the physical processes.

There exists a substantial body of work on physical flood processes in small research catchments where processes can be observed by field campaigns and detailed instrumentation (Grayson & Blöschl, 2000). However, at the regional scale it is much more difficult to isolate flood generating mechanisms. Process analyses of floods at the regional scale usually focus on a single extreme event, rather than on a spectrum of floods. The few studies that have examined the process controls on the entire flood peak sample, as used in regional flood frequency analyses, tend to be much less detailed in terms of the processes they explain. Waylen & Woo (1982), for example,

classified the flood peaks of the Coquihalla River in Canada into two process types, rainfall floods and snowmelt floods, and used antecedent precipitation as the only criterion to discriminate between the two flood generating processes. Sui & Kochler (2001) used observed snow water equivalent to stratify the largest floods on record into events due to rainfall and events due to the combined effect of snowmelt and rain, in a study in Southern Germany. Loukas *et al.* (2000) performed a more detailed classification and inferred the contributions to flooding from rainfall, snow and glacier melt in two catchments in British Columbia, from the runoff components simulated by a catchment model. Hirschboeck *et al.* (2000) focused on the atmospheric conditions associated with floods and performed a detailed analysis of surface and upper weather maps and identified tropical, convective and frontal events in a number of catchments in Arizona, USA.

It appears that most of the studies have focused on one or a few out of many possible indicators for inferring the causative mechanisms of floods. A more comprehensive assessment should examine more than one factor, including catchment conditions as well as the spatial patterns of the causative factors in relation to flooding. At the same time, this approach should be simple enough to make application to a large number of events viable to be of use in regional flood frequency analysis. In this paper this type of approach is proposed. A catchment perspective is adopted, i.e. the focus is on the catchment state and the atmospheric inputs rather than on atmospheric circulation patterns.

## DATA AND METHODS

The study region is Austria, which is hydrologically quite diverse, ranging from lowlands in the east to high alpine catchments in the west. The flood data used in this paper are the maximum annual flood peak series of 490 Austrian catchments from 1971 to 1997.

For information on the catchment state, daily runoff data were compiled for the same period to calibrate and run a catchment model using catchment average precipitation, air temperature and potential evapotranspiration as inputs. Daily precipitation data from 1029 stations, as well as daily air temperature data and potential evaporation estimates from 212 stations, were spatially interpolated by external drift kriging using elevation as additional information, and superimposed on the digital catchment boundaries to derive catchment average values for each day. The model used in this paper is a lumped conceptual rainfall–runoff model, following the structure of the HBV model (Bergström, 1995). The model runs on a daily time step and consists of a snow routine, a soil moisture routine and a routing routine. This model involves a total of 11 calibration parameters. These parameters were calibrated to observed runoff making use of an automated procedure, and the model was verified on a non-overlapping verification period to assure that the model consistently simulated the water balance dynamics in all of the 490 catchments analysed.

In addition to daily rainfall depths, a data set consisting of the depths and durations of a set of observed extreme rainstorms in Austria was used for inferring the flood process types.

## PROCESS TYPES PROPOSED

The flood process types proposed in this paper focus on the catchment state, catchment dynamics and atmospheric inputs rather than on physiographic characteristics of catchments. Therefore no prior assumptions are made as to which process type is more likely to occur in a particular catchment. Five flood process types are proposed roughly following those suggested by Colman (1953): long-rain floods; short-rain floods; flash floods; rain-on-snow floods; and snowmelt floods. Based on expert knowledge in Austria, the following mechanisms are envisaged to be associated with these types.

**Long-rain floods** Rainfall over several days or possibly weeks, including low intensity rainfall, can saturate the catchment and cause high flow conditions. The storage capacity of the catchment is finally exceeded and any additional rain generates a flood event. The rainfall events are synoptic or frontal type storms and often cover a large area of up to several thousands of square kilometres. In Austria some of the most extreme floods on record have been of this type (Gutknecht *et al.*, 2002).

**Short-rain floods** Rainfall of short duration and high intensity occurs and can saturate parts of the catchment. Flood runoff results from a combination of runoff from saturated areas, Hortonian overland flow due to high rainfall intensities, and fast subsurface flow. The event rainfall depth is moderate to large, and wet antecedent conditions enhance the magnitude of this type of event. Depending on the rainfall patterns, the event can be of a local or regional scale.

**Flash floods** Short, high intensity rainfalls, mainly of convective origin, can trigger floods, even if the catchment is in a relatively dry condition. Infiltration excess flow is important, at least in parts of the catchment. The catchment response tends to be very fast, partly because of limited spatial coverage of the catchment by the rainstorm, and partly because most of the flow paths are on the surface. This event is usually a local event, so major floods of this type only occur in small catchments. Flash floods mainly occur in summer or late summer when enough energy is available in the atmosphere to trigger convective storms.

**Rain-on-snow floods** Rain falls on an existing snow cover. Moderate rainfall depths can cause enormous runoff depths as a result of a number of mechanisms. During the rainfall, significant long wave radiation and latent heat inputs enhance snowmelt as compared to dry spells. Antecedent snowmelt may saturate large parts of the catchment facilitating overland flow once rain starts. Large rain-on-snow floods tend to occur at the end of the winter period when river flows are high due to prior snowmelt.

**Snowmelt floods** Snowmelt occurs during warm fair weather spells when snow is on the ground. The melt energy is mainly global radiation at higher altitudes and turbulent heat exchange at lower altitudes. Snowmelt usually occurs over a period of one or two weeks in sequence, saturating the soils, continuously raising the flows and finally causing a flood. Rainfall may occur but is of relatively minor importance. As there is an upper limit of energy available for melt, these floods are never very extreme. Snowmelt floods can only occur in catchments where a large amount of water is stored in the snow pack. They mainly occur in early winter or in spring, depending on the altitude.

## PROCESS INDICATORS

Different flood indicators are used to identify each of the flood process types. Table 1 gives a summary of the envisaged characteristics of the indicators for each of the process types. A simple and important indicator to the type of flood to be expected is the time of the year when a flood occurs (Merz *et al.*, 1999). Other important indicators to flood processes are rainfall depths and snowmelt. As in this study, time series of precipitation data were only available at a daily resolution, 1-day and 3-day liquid precipitation were used as measures of the rainfall inputs for short and long duration storms, respectively. These are catchment average values. To discriminate between rainfall and snowfall a threshold air temperature was used. This threshold reflects the most important temperature and hence elevation effects. Snowmelt was calculated by a degree-day approach in the catchment model and 1-day snowmelt rates were used to assess the presence of snowmelt floods and rain-on-snow floods. In addition to rainfall depths, information on the duration of extreme storms exceeding a depth duration threshold was used as an indicator to storm type and hence the type of runoff response to be expected. The maximum annual floods and the storms were matched by their location and date of occurrence, and it was assumed that matching storms were those producing the flood.

In addition to precipitation controls an important indicator to flood processes is the catchment state prior to floods. Two indicators were examined. The first is the catchment average snow water equivalent, *SWE*. As observations of *SWE* were not available *SWE* simulated by the catchment model were used. The second indicator was runoff

**Table 1** Indicators for identifying flood process types at the regional scale.

Process type	Long-rain floods	Short-rain floods	Flash floods	Rain-on-snow floods	Snowmelt floods
Timing of floods	No pronounced seasonality	No pronounced seasonality	Floods and extreme rainfall mainly in summer or late summer	Often occur during transition between cold and warm periods	Floods in spring to summer
Storm duration	Long duration (>1-day)	Duration of several hours to 1 day	Short duration (<90 min), high intensities	Moderate rainfall events can cause large floods	Rainfall unimportant
Rainfall depths, snow melt	Substantial rainfall depths	Moderate to substantial rainfall	Small to moderate rainfall depths	Snow melt and rainfall	Snowmelt, no or minor rainfall
Catchment state ( <i>SWE</i> , soil moisture)	Wet due to persistent rainfall	Wet for large flood events	Any	Wet, snow covered	Wet, snow covered
Runoff response dynamics	Slow response	Fast response	Flashy response	Responses range from fast to slow	Medium or slow response
Spatial coherence	Large spatial extent of storms and floods (>10 <sup>4</sup> km <sup>2</sup> )	Local or regional extent	Limited spatial extent of storms and floods (<30 km <sup>2</sup> )	Limited to areas of snow cover	Medium spatial extent of floods

at the regional scale for the time period of interest, the catchment average values of coefficient index given by the catchment model to reflect the average soil moisture conditions of each catchment on each day.

Runoff response characteristics can vary significantly both between catchments and between events for the same catchment. As high resolution rainfall and runoff data were not available for all the catchments, the catchment response characteristics for all the maximum annual floods on record were inferred from the ratio of the maximum annual flood peak and the average daily runoff on the day the flood peak occurred. For a slow catchment response this ratio is close to unity, while for a flash flood this ratio is much larger than unity.

Another important characteristic is the spatial extent and location of the region that is covered by the same flood. Shape and location of the spatial coverage of events can provide information about flood processes in addition to the overall extent. The spatial extent and location of any one event were measured by the spatial coherence of maximum annual flood peaks. It was assumed that maximum annual floods occurring on the same (or following) day in catchments that are close to each other (<50 km distance between catchment centroids) were the result of the same event. Using this assumption, clusters of catchments can be defined where each cluster represented one flood event.

## **PROCESS CLASSIFICATION**

The key idea of the classification approach proposed in this paper is to combine a number of process indicators to infer the causative flood mechanisms. Each process indicator discussed above represents one or a few aspects of the flood producing processes. While a single characteristic may not be a unique fingerprint of that process, a combination of different sources of information is likely to much better allow the identification of processes.

Classifications are usually based on a combination of rules and data evidence (e.g. König & Sturm, 1998). The relationships between flood indicators and process types are very complex, so the development of quantitative rules is not straightforward. Therefore a manual classification procedure of flood process types is chosen in this study. The manual approach allows the capture of subtleties of interactions of process indicators not easily incorporated into a quantitative classification scheme.

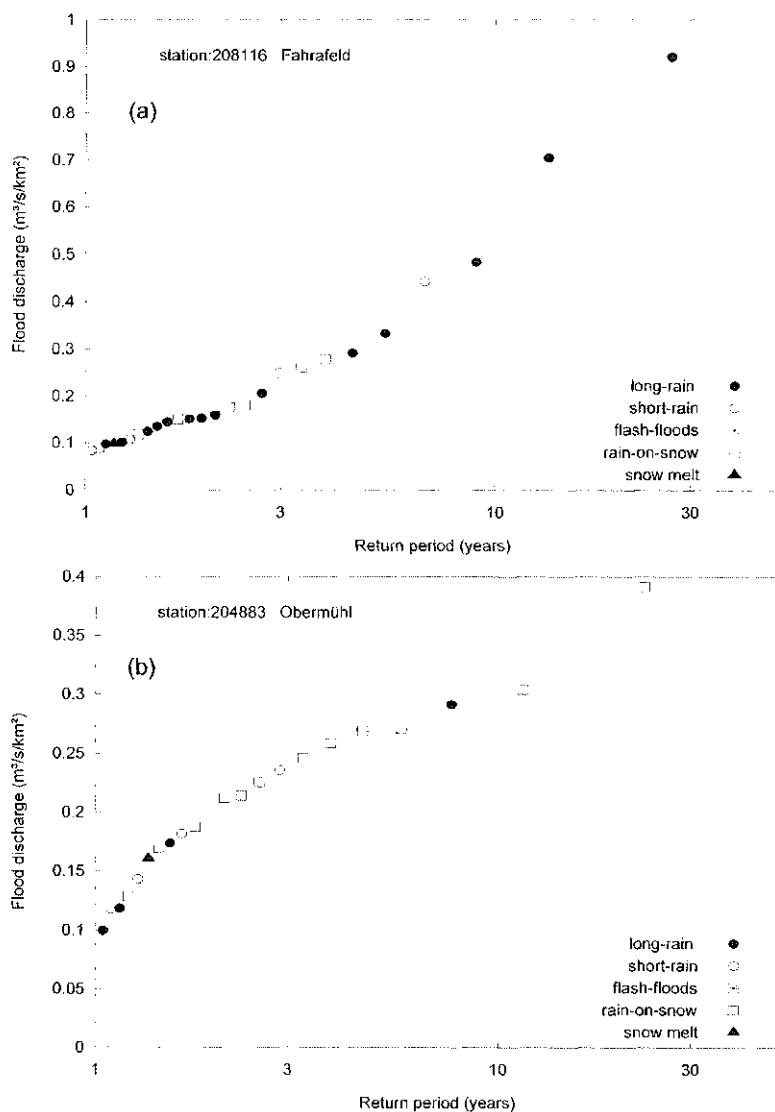
All observed flood peaks were classified on a flood event basis. As it was assumed that maximum annual floods occurring on the same (or the following) day in catchments that are close to each other were the result of the same event, the same flood process type was also assigned to all of these annual floods. This means that each cluster of the coherency analysis is associated with one process type. The database consisted of a total of 11 518 observed maximum annual flood peaks in 490 Austrian catchments for the years 1971–1997. Based on the coherency clustering, these peaks resulted in 2266 flood events, which were then classified.

The main tool, which was used in the classification procedure, were diagnostic maps. The maps covered all of Austria. For each flood event, the maps contained the information about all indicators in a manner such that grasping the essence of the flood processes was a matter of a few minutes for the analyst. Each map consisted of different layers representing the different flood indicators discussed above.

## RESULTS

### Classification results of flood magnitudes

Figure 1 shows two examples of flood frequency curves of the catchments analysed. The symbols indicate the flood process types found by the approach proposed in this paper. Figure 1(a) relates to the Fahrafeld catchment (186 km<sup>2</sup> catchment area) in the eastern most part of the Alps near Vienna. Out of the 26 maximum annual flood peaks



**Fig. 1** Flood frequency plots with the process types indicated. (a) Triesting at Fahrafeld, 186 km<sup>2</sup> catchment area; (b) Kleine Mühl at Obermühl, 199 km<sup>2</sup> catchment area.

observed, 14 flood peaks were associated with long-rain floods, 3 with short-rain, 8 with rain-on-snow and 1 with snowmelt. Figure 1(b) shows the flood frequency curve for the Obermühl catchment (199 km<sup>2</sup> catchment area) in the Mühlviertel region in northern Austria. Out of the 21 maximum annual flood peaks observed, 4 flood peaks were associated with long-rain floods, 4 with short-rain, 12 with rain-on-snow and 1 with snowmelt. The shapes of the flood frequency curves in the two catchments are significantly different. For the Fahrafeld catchment the curve steepens with increasing return period, while in the Obermühl catchment it appears to flatten out at large return periods. It is likely that these differences are closely related to the differences in the process types. As the melt water release is limited by the available energy one would expect the tail of the distribution of the rain-on-snow-dominated catchments to be flatter than that of the rainfall-dominated catchments. In the case of the Fahrafeld catchment the three largest floods in this record were all long-rain floods. However, in the case of the Obermühl catchment the two largest floods were rain-on-snow floods. In both catchments the short-rain floods and snowmelt floods were among the smallest flood peaks on record and flash floods did not occur.

Table 2 shows the classification results of the 2266 flood events of the years 1971 to 1997 which gives the following breakdown: 783 (35%) long-rain floods, 597 (26%) short-rain floods, 302 (13%) flash floods, 430 (19%) rain-on-snow floods and 154 (7%) snowmelt floods. This means that almost two thirds of the flood events were long-rain and short-rain floods.

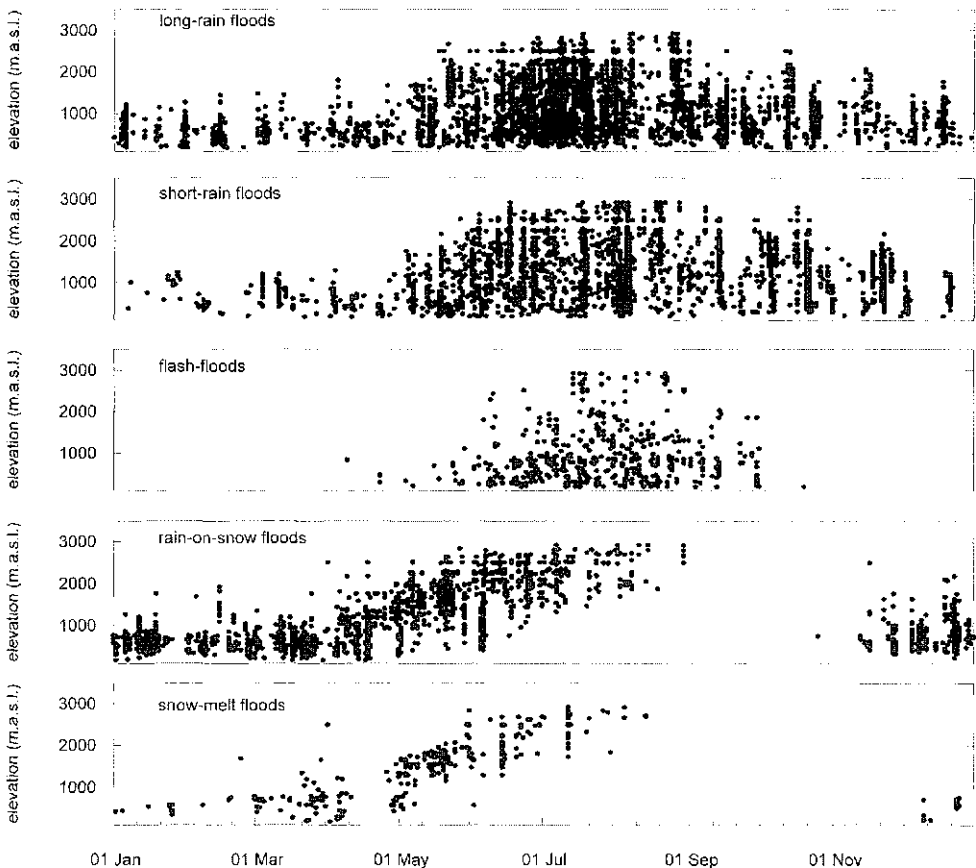
In Table 2, whether the relative frequency of the process types changes with the magnitude of the event is examined for all 490 catchments. Table 2 indicates that there are indeed significant changes in the frequency. In the case of the short-rain type, 12.5% of the peaks of this type were larger than the 10-year flood in each catchment. In contrast, for the rain-on-snow type, only 3.3% were larger than the 10-year flood and for the snow-melt type only 1.4% were larger than the 10-year flood. This means that large floods are quite frequently caused by short-rain events, large floods are rarely caused by rain-on-snow events and they are almost never caused by snowmelt events. Again, these differences would be expected because of the limited energy available for melt water release.

**Table 2** Results of the flood type classification of maximum annual floods in 490 Austrian catchments, 1971–1997. *MAF* is the mean annual flood.

Process type	Long-rain floods	Short-rain floods	Flash floods	Rain-on-snow floods	Snowmelt floods	All types
Number of events	783	597	302	430	154	2266
Number of flood peaks <MAF	2511 (50.6%)	1281 (39.7%)	274 (50.3%)	1398 (57.4%)	248 (71.5%)	5712 (49.6%)
Number of flood peaks >MAF and <10-year flood	2051 (41.3%)	1541 (47.8%)	225 (41.3%)	957 (39.3%)	94 (27.1%)	4868 (42.3%)
Number of flood peaks >10-year flood	404 (8.1%)	403 (12.5%)	46 (8.4%)	80 (3.3%)	5 (1.4%)	938 (8.1%)
Total number of flood peaks	4966 (100%)	3225 (100%)	545 (100%)	2435 (100%)	347 (100%)	11518 (100%)

## Process types and seasonality

All process types exhibit seasonal patterns in the flood occurrence that are mainly related to the annual fluctuations in air temperature. Air temperature also exhibits a strong altitudinal dependence. In Fig. 2 the mean elevation of each catchment has therefore been plotted vs the day of occurrence of the maximum annual flood. Long-rain floods and short-rain floods occur throughout the year but in summer they are more frequent and extend to higher elevations. Flash floods only occur in summer, when enough energy is available for convective storms, and they extend up to the highest altitudes of the study region of 3000 m a.s.l. Rain-on-snow floods and snowmelt floods exhibit a narrow altitudinal range of occurrence which varies with the time of year. In winter, both types occur in catchments lower than 1000 m a.s.l. The altitudinal range gradually increases during spring and extends from 2000 to 3000 m a.s.l. in summer. Both rain-on-snow and snowmelt floods appear to occur only within a limited range of temperature conditions for which a snow cover exists, but snowmelt and/or rain may occur.



**Fig. 2** Average catchment elevation plotted vs the date of occurrence of the maximum annual flood, stratified by process type.

## DISCUSSION AND CONCLUSIONS

There are a number of reasons that suggest that the classification procedure has resulted in a realistic stratification of flood peaks into flood process types. First, in the visual inspection of the diagnostic plots of flood events, it was in most cases quite clear which type to assign. This was because a number of indicators were available that could be used to identify the process type. Second, most of the characteristics of the floods obtained by the classification procedure could be interpreted well, based on hydrological reasoning, and they are consistent with experience in the study region.

The strength of the approach proposed in this paper is that it is applicable at the regional scale where less detailed information is available than in individual catchment studies. It is applicable in a flood frequency context where the classification of a large number of events is needed. A total of 11 518 flood peaks have been classified in this study, which is certainly a number that makes the approach appealing to regional flood frequency studies. Another important characteristic of the proposed approach is that it is viable in the presence of incomplete data. If, say, hourly data were available for all streamgauges and for all raingauges during the entire study period, a more rigorous classification would be straightforward. This is not the case in the study region and is likely not the case in most other regions of the world. These traits of the approach have been achieved by using a combination of different indicators, derived from independent sources of information as available. Some of the indicators are complementary, which allows for a more detailed classification than would be possible by a single indicator.

Long-rain floods have been found to be the most common type of maximum annual floods in Austria. In a humid climate such as in Austria this result is not surprising. Most catchments in Austria appear to possess a relatively large storage capacity, so significant rainfall depths are needed to produce a major flood. Persistence of a precipitation system is a key element for generating large floods in many climatic regions of the world (Colman, 1953; Hirschboeck *et al.*, 2000). Flash floods associated with high intensity storms of very short duration (i.e. less than a few hours) are less frequent. This is likely a combined result of the rainfall characteristics of the Austrian climate where convective storms are usually not very extreme, and relatively dry catchment conditions prevail in summer when these types of events occur. It should also be noted that the gauged catchments analysed in this paper are not very small, with the median catchment size on the order of 100 km<sup>2</sup>. If smaller catchments were analysed it is likely that the frequency of flash floods would be significantly higher. Rain-on-snow is an important causative mechanism. A similar finding was made in a study from southeastern Germany (Sui & Koehler, 2001). Floods that are due to snowmelt alone are the least frequent process type producing maximum annual floods.

The relative contribution of the process types changes with the flood magnitude. In a given catchment, large floods are quite frequently caused by short-rain events, large floods are rarely caused by rain-on-snow events and they are almost never caused by snowmelt events. There are 938 floods with return periods of 10 years or more in the data set, but only five of them (i.e. only 0.5%) were snowmelt floods as opposed to 3% if all flood magnitudes are considered. This shift in the importance of snowmelt floods would be expected because of the limited energy available for melt water release.

There exist a number of logical extensions of the work reported in this paper. For this study a catchment perspective is adopted, and it will be important to complement this research by a focus on atmospheric circulation patterns associated with the maximum annual floods, similar to the analyses of Hirschboeck *et al.* (2000), for example. Ultimately, the flood process typology should be applied to improve the at-site and regional estimation of flood probabilities.

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