# A process typology of regional floods

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[1] We propose a framework for identifying types of causative mechanisms of floods. The types are long-rain floods, short-rain floods, flash floods, rain-on-snow floods, and snowmelt floods. We adopt a catchment perspective, i.e., the focus is on the catchment state and the atmospheric inputs rather than on atmospheric circulation patterns. We use a combination of a number of process indicators, including the timing of the floods, storm duration, rainfall depths, snowmelt, catchment state, runoff response dynamics, and spatial coherence. On the basis of these indicators and diagnostic regional plots we identify the process types of 11,518 maximum annual flood peaks in 490 Austrian catchments. Forty-three percent of the flood peaks are long-rain floods, only 3% are snowmelt floods, and the relative contribution of the types changes with the flood magnitude. There are pronounced spatial patterns in the frequency of flood type occurrence. For example, rain-on-snow floods most commonly occur in northern Austria. Runoff coefficients tend to increase with rainfall depth for long-rain floods but are less dependent of rainfall depth and exhibit much larger scatter for flash floods. All types exhibit seasonal patterns, both in terms of flood magnitudes and catchment altitudes of flood occurrence. The coefficient of variation (CV) of the flood samples stratified by process type decreases with catchment area for most process types with the exception of flash floods for which CV increases with catchment area. *INDEX TERMS:* 1821 Hydrology: Floods; 1854 Hydrology: Precipitation (3354); 1860 Hydrology: Runoff and streamflow; *KEYWORDS:* flood, flood process, classification, catchment state, Austria

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## 1. Introduction

[2] Understanding the physical processes giving rise to floods of a given probability of occurrence is among the most intriguing areas of catchment hydrology. Not only are these processes complex and controlled by a range of variables including rainfall regime, snowmelt, state of the catchment and catchment characteristics but also their interaction is intricate and has so far defied detailed analyses at the regional scale. Because of this complexity, analyzing 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. These statistical distributions represent the cumulative effect of all of the flood producing processes and their interaction in a global way and are therefore reasonably accurate descriptions of flood probabilities for the conditions the sample is representative of. However, as statistical distribution functions are very simple (black box) representations of the hydrological system they do not provide any insight into the physical causes of the floods and how they relate to flood probabilities. Also, from a predictive perspective it is likely that, because of the lack of physical basis, 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. As *Klemeš* [1993, p. 168] pointed out "If more light is to be shed on the probabilities of hydrological extremes, then it will have to come from more information on the physics of the phenomena involved, not from more mathematics".

[3] 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 [e.g., *Dunne*, 1983; *Anderson and Burt*, 1990; *Peschke et al.*, 1999; *Grayson and Blöschl*, 2001]. However, at the regional scale it is much more difficult to isolate flood generating mechanisms both in time (summer vs. winter, rainfall vs. snowmelt, etc.), and also in space (different parts of the landscape, different climate, soils, vegetation, land use, etc.). Process analyses of floods at the regional scale usually focus on flood routing and inundations rather than on the flood generation processes and, more importantly, the focus is usually on a single extreme event, rather than on a spectrum of floods [e.g., *Smith et al*, 1996; *Grünewald*, 1998; *Grebner and Roesch*, 1999]. 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. Past attempts have evolved along two separate lines that one may term upward (or model based) approaches and downward (or data based) approaches [*Klemeš*, 1983].


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[4] In the upward approach to analyzing flood process controls the idea is to combine a stochastic rainfall model with a deterministic runoff model, based on derived distribution theory or Monte Carlo simulations. The processes envisaged are built into the models and one hopes that the flood frequency curve so compiled reflects the composite behavior of the underlying physical processes. Examples of this approach include those by *Blöschl and Sivapalan* [1997] and *Robinson and Sivapalan* [1997], who using different models, related flood generation processes to flood frequency characteristics as a function of catchment area. The limitation of this approach is that it is not always clear to which extent the individual model components match the actual hydrologic processes interacting in the landscape. An alternative is the downward approach in which flood peak samples are stratified into two or more classes of flood types based on flood characteristics observed in the field. In a second step, the stratified samples are interpreted in terms of the processes that are likely to have led to a particular flood frequency behavior.

[5] The simplest way of stratifying the samples is by subdividing a region into a number of sub-regions in each of which one process may dominate. Example of this approach include those by *Gupta and Dawdy* [1995], who examined sub-regions where either rain induced or snowmelt induced floods dominated, and *Piock-Ellena et al.* [2000], who isolated eight sub-regions in Austria based on cluster analyses of seasonality and other flood indicators. In both studies, the flood statistics in the sub-regions were then interpreted in terms of prevailing flood mechanisms. However, often, a mix of causative mechanisms may be responsible for floods at the same site. Floods may be due to extreme rainfall, rapid snowmelt, or rain on snow events. The atmospheric patterns leading to rainfall may also differ. The statistical attributes of these events are often quite different. *Hirschboeck* [1987], for example, performed a detailed analysis on causative mechanisms of floods in a number of catchments in Arizona based on surface and upper weather maps [*Hirschboeck*, 1988]. This scheme was updated by *House and Hirschboeck* [1997] and simplified into three event types (tropical, convective and frontal events). The body of work on causative mechanisms allowed *Hirschboeck* [1987] and *Alila and Mtiraoui* [2002] to examine the flood statistics for each group of events and derive hydroclimatically defined mixed distributions in flood series. Other studies have focused on catchment conditions rather than on the atmospheric conditions associated with flood events. *Waylen and Woo* [1982] 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 and Koehler* [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.

[6] 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 atmospheric and 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 the make application to a large number of events viable to be of use in regional flood frequency analysis. In this paper we propose this type of approach. Specifically, the aim of this paper is (1) to propose a framework for identifying process types of causative mechanisms of floods, (2) to examine the viability of this typology for a large number of events and catchments, and (3) to analyze the statistical characteristics for each of the event types. We adopt a catchment perspective, i.e., the focus is on the catchment state and the atmospheric inputs rather than on atmospheric circulation patterns. In section 2 we summarize the data and the model used. In sections 3 to 5 we outline the proposed typology, process indicators and the approach to identifying the types. In section 6 the results of the classification are reported including the frequency of the events, their event characteristics and the associated flood frequency characteristics. Section 7 concludes this paper with a discussion and a summary of the main findings.

## 2. Data and Methods

[7] The study region is Austria which is hydrologically quite diverse, ranging from lowlands in the east to high alpine catchments in the west. Elevations range from less than 200 m above sea level (asl) to more than 3000 m asl. Mean annual precipitation is less than 400 mm/year in the east and almost 3000 mm/year in the west. Land use is mainly agricultural in the lowlands, forested in the medium elevation ranges, while alpine vegetation and rocks prevail in the highest catchments.

[8] The flood data used in this paper are maximum annual flood peak series in Austria from 1971 to 1997. While multiple large floods occasionally occur in a single year, partial duration series were not available in the study area. We carefully screened all maximum annual flood peak records for data errors and removed records with significant anthropogenic effects [*Blöschl et al.*, 2000a]. This screening resulted in reliable flood series for 490 catchments. The areas of these catchments range from 3 km$^2$ to 30,000 km$^2$ with a median of 148 km$^2$. We also used daily precipitation data from 1029 stations, as well as daily air temperature data and potential evaporation estimates from 212 stations. Potential evaporation was estimated from daily temperature and daily air humidity by a monthly regression equation (*H. Formayer, personal communication*, 2000) and checked against the results of the Penman equation wherever global radiation data were available [*Deutscher Verband für Wasserwirtschaft und Kulturbau* (*DVWK*), 1996]. The daily values of precipitation, air temperature and potential evapotranspiration were spatially interpolated by external drift kriging [*Deutsch and Journel*, 1997] using elevation as additional information, and superimposed on the digital catchment boundaries to derive catchment average values for each day. As precipitation time series were only available on a daily basis we used an additional data set

consisting of the depths and durations of a set of observed extreme rainstorms in Austria [*Gutknecht and Watzinger*, 1999].

[9] For the same period we compiled daily runoff data to calibrate and run a catchment model using catchment average precipitation, air temperature and potential evapotranspiration as inputs. The model used in this paper is a lumped conceptual rainfall-runoff model, following the structure of the HBV model [*Bergström*, 1992, 1995]. The model runs on a daily time step and consists of a snow routine, a soil moisture routine and a routing routine. The snow routine represents snow accumulation and melt by a simple degree day concept. A threshold air temperature discriminates between rainfall and snowfall. Catch deficit of the precipitation gauges during snowfall is corrected by a snow correction factor. The soil moisture routine represents runoff generation and changes in the soil moisture state of the catchment and involves three parameters, the maximum soil moisture storage, a parameter representing the soil moisture state above which evaporation is at its potential rate, termed the limit for potential evaporation, and a parameter in the non-linear function relating runoff generation to the soil moisture state, termed the non-linearity parameter. The response function represents runoff routing on the hillslopes, and consists of an upper and a lower soil reservoir. Excess rainfall enters the upper zone reservoir and leaves this reservoir through three paths, outflow from the reservoir with a fast storage coefficient, percolation to the lower zone with a constant percolation rate, and, if a threshold of the storage state is exceeded, through an additional outlet with a very fast storage coefficient. Water leaves the lower zone with a slow storage coefficient. The outflow from both reservoirs is then routed by a triangular transfer function representing runoff routing in the streams. This model involves a total of 11 calibration parameters. We calibrated these parameters to observed runoff making use of an automated procedure [*Duan et al.*, 1992] and verified the model on a non-overlapping verification period to assure that the model consistently simulates the water balance dynamics in all of the 490 catchments analyzed. A more detailed description of the model and its application to the catchments of this paper is given by *Merz and Blöschl* [2003].

## 3. Process Types Proposed

[10] The flood process types we propose in this paper focus on the catchment state, catchment dynamics and atmospheric inputs rather than on physiographic characteristics of catchments. We therefore make no prior assumptions on which process type is more likely to occur in a particular catchment. We propose five flood process types roughly following those suggested by *Colman* [1953] and other authors [e.g., *Naef*, 1985]: long-rain floods; short-rain floods; flash floods; rain-on-snow floods; and snowmelt floods. On the basis of our experience in Austria, we envisage the following mechanisms to be associated with theses types.

### 3.1. Long-Rain Floods

[11] 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 up to several thousands of square kilometers. In Austria some of the most extreme floods on record have been of this type [*Gutknecht et al.*, 2002].

### 3.2. Short-Rain Floods

[12] 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, runoff from parts of the catchment where the rainfall intensities exceed infiltration capacity and from 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.

### 3.3. Flash Floods

[13] Short, high intensity rainfalls, mainly of convective origin, can trigger floods even if the catchment is in a relatively dry condition. Locally, the rainfall intensities exceed infiltration capacity. The catchment response tends to be very fast, partly because of limited spatial coverage of the catchment by the rainstorm, and partly because of most of the flow paths being 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.

### 3.4. Rain-on-Snow Floods

[14] 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. In Alpine catchments, large rain-on-snow floods tend to occur at the end of the winter period when river flows are high due to prior snowmelt. In the lowlands, large rain-on-snow floods can also occur in early winter when snowfall events, snowmelt events and rain events alternate.

### 3.5. Snowmelt Floods

[15] Snowmelt occurs during fair weather periods often associated with a rapid increase in air temperature. The melt energy is mainly global radiation in higher altitudes and turbulent heat exchange in 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 snowpack. They mainly occur in early winter or in spring, depending on the altitude.

[16] It is important to note that we do not intend to identify local-scale processes (such as infiltration characteristics) nor do we intend to identify hillslope-scale processes (such as infiltration excess runoff generation, subsurface storm flow etc.). Our intention is to identify catchment-scale

**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 | mainly occur at the change 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, snowmelt | substantial rainfall depths | moderate to substantial rainfall | small to moderate rainfall depths | snowmelt and rainfall | snowmelt, no or minor rainfall |
| Catchment state (SWE, soil moisture) | wet due to persistent rainfall | wet for large flood events | dry or wet | wet, snow covered | wet, snow covered |
| Runoff response dynamics | slow response | fast response | flashy response | fast or slow response | medium or slow response |
| Spatial coherence | large spatial extent of storms and floods (>$10^4$ km$^2$) | local or regional extent | limited spatial extent of storms and floods (<30 km$^2$) | limited to areas of snow cover | medium spatial extent of floods |

processes. These can be interpreted as a mix of small-scale processes or one can choose to directly conceptualize them at the catchment scale. We believe that it is perfectly adequate to conceptualize processes at larger than laboratory scales. This is done in a number of branches of Earth sciences [see, e.g., *de Rosnay*, 1979] and there is a growing body of literature in hydrology that emphasizes the conceptualization of processes directly at the catchment scale [e.g., *Klemeš*, 1983; *Sivapalan*, 2003].

[17] It is also likely that these processes types do not have sharp boundaries, neither in their definition nor the conceptual picture of the suite of mechanisms and processes involved. The differences between long-rain and short-rain or short-rain and flash floods or rain-on-snow and snowmelt are gradational rather than sharp process boundaries. This is the case with most classifications in hydrology and other Earth sciences where heterogeneity is involved. For example, at the local scale, matrix and preferential flows are often classified as separate infiltration regimes but, in practice, both may occur at the same time even though one of them is likely to dominate [e.g., *Zehe and Flühler*, 2001]. Similarly, at much larger scales, the definition of El Niño years is gradual and the classification is usually done by setting a rather arbitrary threshold of a climatic index [e.g., *Piechota and Dracup*, 1996]. These types of classifications are useful as they will capture the bulk of the cases notwithstanding the existence of a number of borderline cases.

## 4. Process Indicators

[18] In the following we present the flood process indicators we have used to identify each of the flood process types. We illustrate the potential of these indices by showing the spatial patterns of the statistical climatological characteristics of some of these indices, i.e., their values averaged over the entire study period. Table 1 gives a summary of the envisaged characteristics of the indicators for each of the process types.

### 4.1. Timing of Floods

[19] The time of the year a flood occurs is a simple and important indicator to the type of flood to be expected [*Jain and Lall*, 2000; *Merz et al.*, 1999b]. Figure 1 shows the average seasonality of maximum annual flood peaks in Austria. Following *Burn* [1997], we have defined $D$ as the date of occurrence of the flood peak where $D$ = 1 for 1 January and $D$ = 365 for 31 December. $D$ can be plotted in polar coordinates on a unit circle with angle $\Theta = D\ 2\pi/365$. For all events in a maximum annual flood peak series of a catchment, the direction $\overline{\Theta}$ of the average vector from the origin indicates the mean date of occurrence of the flood peak values around the year, while the length $r$ of that vector is a measure of the variability of the date of occurrence. Values of $r$ range from $r$ = 0 (uniformly distributed around the year) to $r$ = 1 (all flood peaks occurring on the same day). The colors in Figure 1 indicate $\overline{\Theta}$, and the intensity indicates $r$. Weak, medium and strong seasonalities are defined as $r < 0.3$, $0.3 \leq r \leq 0.7$ and $r > 0.7$, respectively. In the high Alpine catchments in the west of the country, floods tend to occur in summer showing a strong seasonality, which suggests the presence of snow and glacier melt floods. In the north, weak seasonalities suggest that there is no single dominant process for a given catchment and different floods can be generated by different processes. The spring floods in the very north of the country suggest that both early snowmelt and rain-on-snow are likely to occur in these catchments. In Carinthia, in the very south of Austria, floods tend to occur in late autumn which may be related to the advection of moist air from the Mediterranean south of Austria.

### 4.2. Storm Duration

[20] Storm duration, in any one catchment, is an indicator for storm type and hence the type of runoff response to be expected. As a result of topographic and climatologic effects there may exist major spatial differences in the characteristics in the storm types. Figure 2 shows the spatial patterns of the average duration of extreme storms that have produced a maximum annual flood in Austria. In the database used, an extreme storm is defined as a storm exhibiting a rainfall depth $P \geq (5*t)^{1/2}$ where $P$ is in mm and $t$ is rainfall duration (min) [*Gutknecht and Watzinger*, 1996]. We matched the maximum annual floods and the storms by their location and date of occurrence, and assumed matching storms to be those producing the flood. Short durations of storms causing floods mainly occur in south-eastern Austria where short convective storms are known to be important for flood generation. In contrast, long duration storms occur in north-western Austria at the northern fringe of the Alps. As most flood producing weather systems approach from the north-west, this zone is

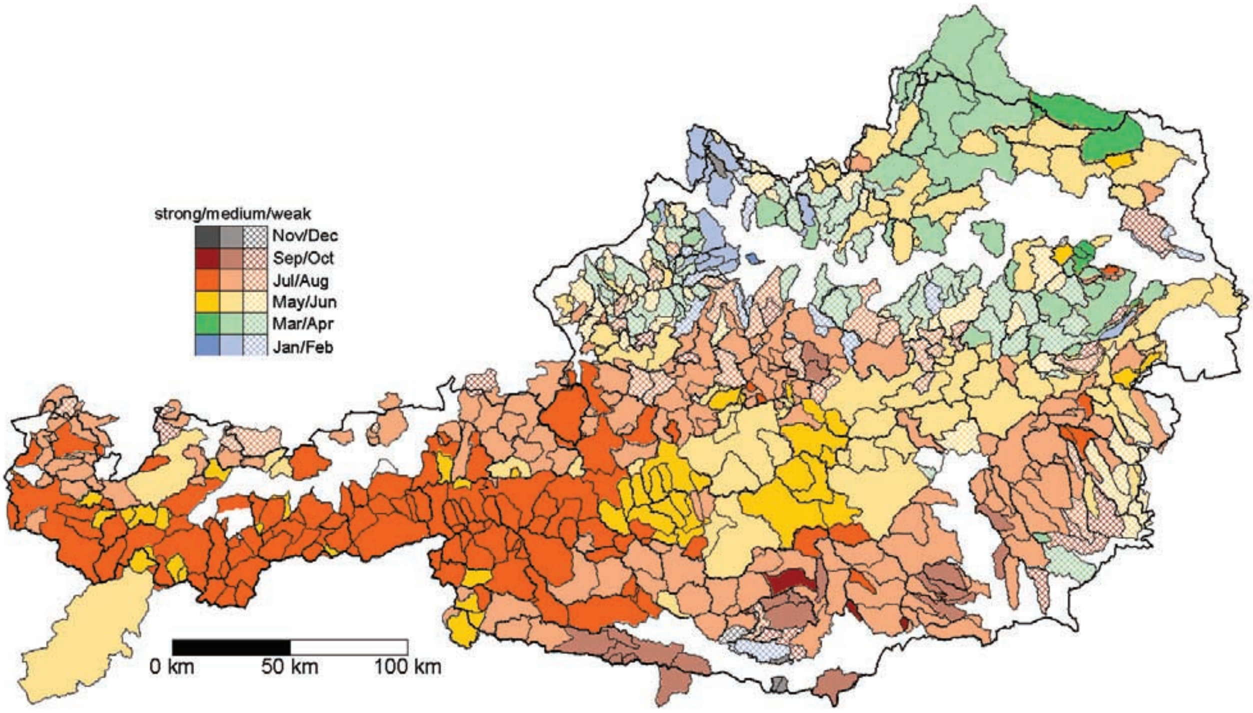


**Figure 1.** Average seasonality of maximum annual floods in Austria (average of 1951–1997). The colors represent the mean date of flood occurrence, and the intensity of the color indicates the degree of seasonality. For nested catchments the seasonalities of the smaller catchments have been plotted on top of

an area of orographic enhancement effects where synoptic rainfalls tend to be most important for flood generation.

### 4.3. Rainfall Depths and Snowmelt

[21] Rainfall depths are usually largest in the north-west of the country, mainly as a result of the orographic effects mentioned above. At the northern fringe of the Alps in the north-west of Austria, daily rainfall associated with a return period of 100 yrs is on the order of 150 mm [*Merz et al.*, 1999a]. In Carinthia, in the very south of Austria, similar rainfall rates can occur. In the central part of Austria which is topographically much more sheltered, 100 yr daily

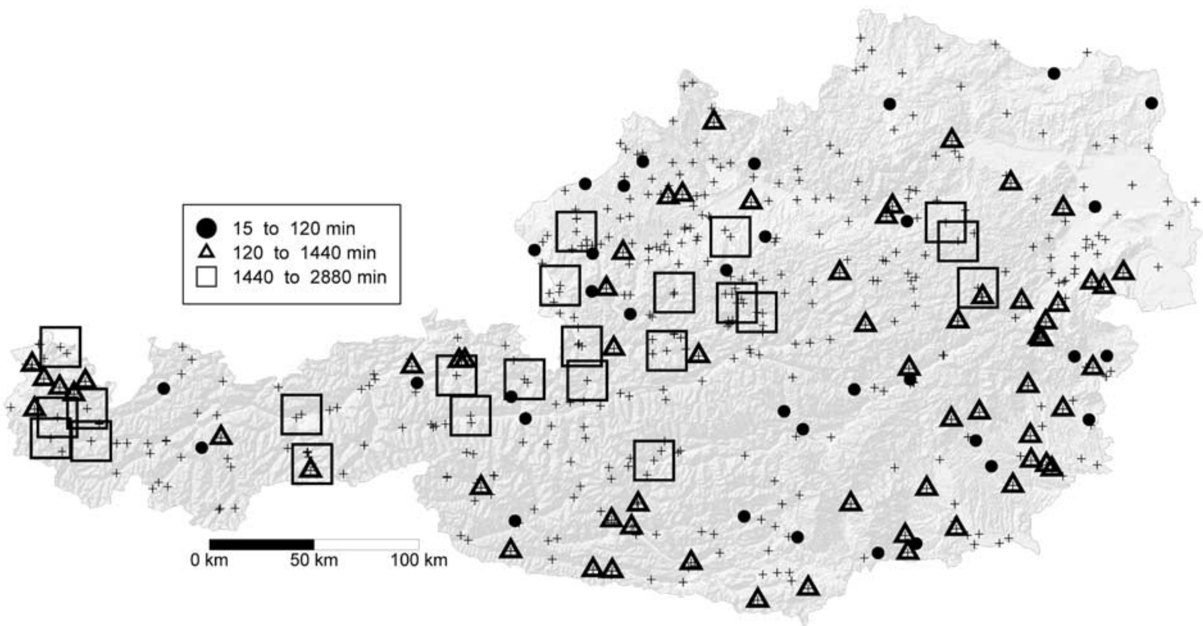


**Figure 2.** Average duration of extreme storms that have produced a maximum annual flood in Austria (average of 1951–1997). Stations without any observed extreme storm are marked by plusses.

rainfall rates are only 90 mm or less. As time series of precipitation data were only available at a daily resolution we used 1-day and 3-day liquid precipitation as measures of the rainfall inputs for short and long duration storms, respectively. These are catchment average values. To discriminate between rainfall and snowfall we used threshold air temperatures. This thresholding reflects the most important temperature and hence elevation effects. On the basis of the detailed analysis of the state of precipitation in the Swiss Alps given by *Rohrer* [1989] we assumed snow fall to occur at air temperatures below 0°C, rainfall at air temperatures above 2°C, and mixed rain-snow fall between these limits. Snowmelt was calculated by a degree day approach of the catchment model and 1-day snowmelt rates were used to assess the presence of snowmelt floods and rain-on-snow floods.

### 4.4. Catchment State

[22] An important indicator of flood processes is the catchment state prior to floods. We examined two indicators. The first is the catchment average snow water equivalent, *SWE*. In typical years, maximum winter snow water equivalents range from more than 500 mm in the Alps in the west of Austria to only a few millimeters in the lowlands in the east of the country. As observations of *SWE* were not available at the regional scale for the time period of interest, we used the catchment average values of *SWE* simulated by the catchment model. The second indicator we used was a runoff coefficient value to reflect the average soil moisture conditions of each catchment on each day. This runoff coefficient $r_c$ was calculated from the catchment model simulations in the following way.

$$r_c = \frac{\Delta S_{uz}}{P_r + P_m} \cdot \frac{Q_0 + Q_1}{Q_g} \tag{1}$$

where $\Delta S_{uz}$ is the contribution of rain and snowmelt to runoff, calculated as a function of soil moisture of the top layer, $P_r$ is rainfall, $P_m$ is snowmelt, $Q_0$ and $Q_1$ are the outflows from a very fast and a fast soil reservoir, respectively, and $Q_g$ is the sum of the outflows from the very fast, the fast and a slow reservoir. For each of the fluxes in equation (1) daily values were used. The first term in equation (1) represents the relative contribution to both direct runoff and base flow, so the second term was introduced as an adjustment to approximate the contribution to direct storm runoff only. The values of $r_c$ are larger than what one would expect for event runoff coefficients estimated from comparing direct runoff with event rainfall. Values of $r_c$ lower than 0.5 indicate relatively dry catchment conditions.

### 4.5. Runoff Response Dynamics

[23] Runoff response characteristics can vary significantly both between catchments and between events for the same catchment [e.g., *Kirnbauer et al.*, 2001]. As high resolution rainfall and runoff data were not available for all the catchments, we used a proxy measure to infer the catchment response characteristics for all the maximum annual floods on record. We calculated the ratio of the maximum annual flood peak and the average daily runoff on the day the flood peak occurred. For slow catchment response this ratio is close to unity while for a flashy flood this ratio is much larger than unity. To facilitate the comparability of this proxy value we calculated the time of concentration *tc* from it, by assuming that the hydrograph shape can be approximated by the response *Q*(*t*) of a linear reservoir with time constant *tc* to a constant rainfall of duration *tc* [*Merz et al.*, 1999a]:

$$\begin{aligned} Q(t) &= C \cdot \left(1 - e^{-t/tc}\right) \qquad & t < tc \\ Q(t) &= Q(tc) \cdot e^{-\frac{t-tc}{tc}} \qquad & t \geq tc \end{aligned} \tag{2}$$

This is consistent, for example, with the rational formula assumptions. The ratio of the maximum annual flood peak and the average daily runoff has been calculated by integrating the hydrograph:

$$\frac{Qs}{Qm} = \frac{(1 - e^{-1}) \cdot H}{tc \cdot \left(1 - (1 - e^{-1}) \cdot e^{\frac{-H/2}{tc}}\right)} \qquad \text{for } tc \leq H/2$$

$$\frac{Qs}{Qm} = \frac{(1 - e^{-1}) \cdot H}{\frac{H}{2} + tc \cdot \left(1 - e^{\frac{H/2 - tc}{tc}} - (1 - e^{-1}) \cdot e^{\frac{-H/2}{tc}}\right)} \qquad \text{for } tc > H/2 \tag{3}$$

where *H* is 24 hrs. The time of concentration has then been estimated by inverting equation (3) iteratively. As we are not interested in the catchment-scale dependence of the time of concentration one usually encounters in runoff data [*Melone et al.*, 2002], we standardized *tc* by catchment area

$$tc^* = \frac{tc}{5 \cdot A^{0.35}} \tag{4}$$

where *tc** is the standardized time of concentration (hrs) and *A* is the catchment area (km$^2$). The power in equation (4) has been chosen according to typical catchment-scale dependences of *tc* [*Melone et al.*, 2002], while the factor has been chosen in a way that the median value of *tc** in Austria is unity. The *tc** values averaged over all maximum annual floods of the years 1971 to 1997 in Austria are shown in Figure 3. The patterns of *tc** are rather patchy, however, some regional differences can be distinguished. Catchments in south-eastern Austria (Styria) tend to exhibit very fast responses (small *tc** represented by dark shading in Figure 3). These are likely due to short convective storms with high intensities, probably with partial storm coverage of the catchments. However, not everywhere can *tc** be interpreted on the basis of storm duration. Near Salzburg in the north-west of Austria, a number of catchments exhibit large *tc** values and these can be traced back to lake retention. South of Vienna, in the east of Austria, large *tc** values are a consequence of groundwater effects where the floods are significantly affected by recharge into large porous aquifers. Slowly responding catchments are also located in the very north and in the central parts of Austria.

### 4.6. Spatial Coherence

[24] Another important characteristic is the spatial extent and location of the region that is covered by the same flood. Floods exhibiting a small spatial extent may have been caused by local events such as convective storms and these floods will not be coherent in space. In contrast, floods with a large spatial extent may have been caused by regional

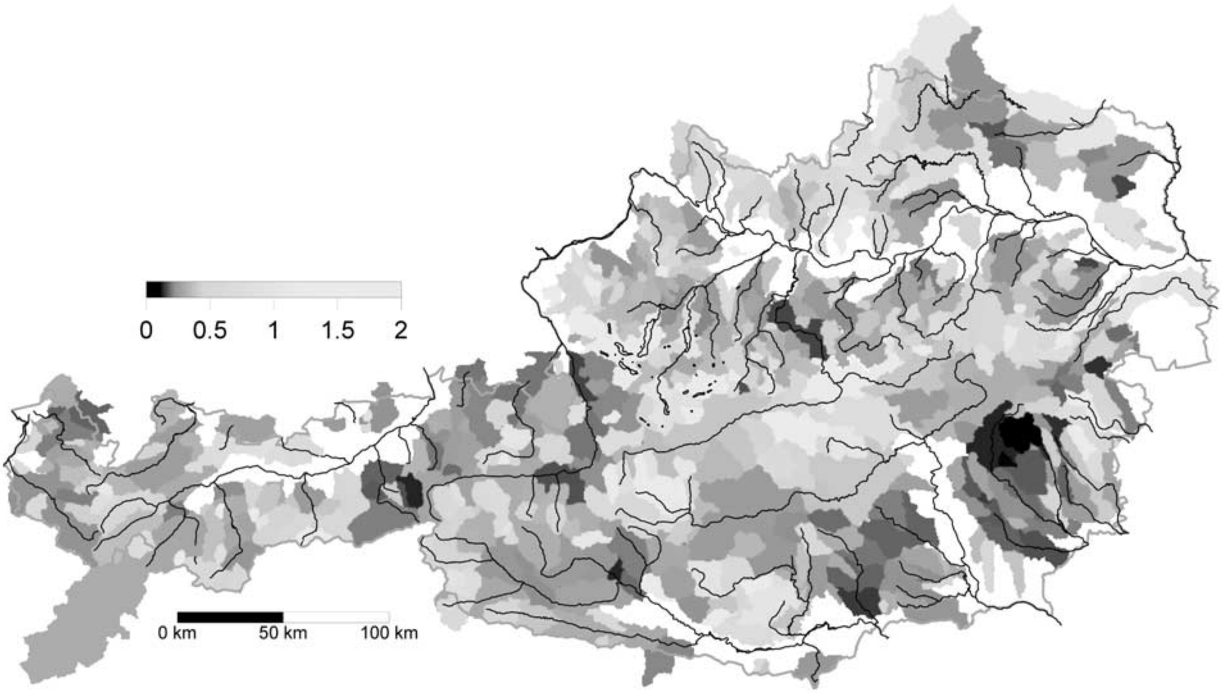


**Figure 3.** Geometric mean of the time of concentration standardized by catchment area (equation (4)) for maximum annual floods in Austria (average of 1971–1997). For nested catchments the times of concentration of the smaller catchments have been plotted on top of those of the larger catchments, and only catchments smaller than 5000 km$^2$ are shown.

processes such as orographic rainfall or regional synoptic events and will be coherent. Shape and location of the spatial coverage of events can provide information about flood processes in addition to the overall extent. We measure the spatial extent and location of any one event by the spatial coherence of maximum annual flood peaks. We assume that maximum annual floods occurring on the same (or following) day in catchments that are close to each other are the result of the same event. Two catchments are considered close to each other if the distance of their centroids is less than 50 km. Using this assumption we were able to define clusters of catchments where each cluster represented one flood event. To visualize the spatial coherence, each cluster was represented by an ellipse which was placed on the center of the cluster. The lengths of the axes were calculated as the mean squared distances of the catchment centroids to the cluster center in both directions, i.e., the second spatial moments of the catchment centroids. Figure 4 shows the spatial coherence of all maximum annual floods in 1990. The month and day of each flood event are given at the centers of the ellipses. The most striking flood event in 1990 was the event of 10 July. The large extent and the location of the ellipse suggest that this flood resulted from synoptic rainfall and orographic enhancement effects. This assessment has been checked against independent information from weather maps provided by the Austrian Central Institute of Meteorology and Geodynamics. The weather maps indicate inflow of moist air from the Atlantic Ocean during early July coupled with a sequence of perturbations on 6, 8, and 10 July. These produced heavy precipitation over larger areas of Central Europe, particularly on the northern fringe of the Alps where the airflows interacted with terrain. Figure 4 also shows that in winter and spring 1990, floods with moderate spatial extents have occurred in the low-altitude catchments of northern Austria. It is likely that snowmelt is an important control for these floods. Local events, i.e., flood events covering only one or a few catchments, mainly occur in summer. It is likely that convective storms have produced these floods.

## 5. Process Classification

[25] 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 an unique fingerprint of that process, a combination of different sources of information is likely to much better allow the identification of processes.

[26] Classifications are usually based on a combination of rules and data evidence. Examples in hydrology include the classification of snow patterns [*König and Sturm*, 1998] and the classification of runoff generation processes [*Peschke et al.*, 1999]. The relationships between flood indicators and process types are very complex, so the development of quantitative rules is not straightforward. We have therefore chosen to adopt a manual classification procedure of flood process types in this study. The manual approach allows us to capture subtleties of interactions of process indicators not easily incorporated into a quantitative classification scheme.

[27] We classified all observed flood peaks on a flood event basis. As we assumed that maximum annual floods

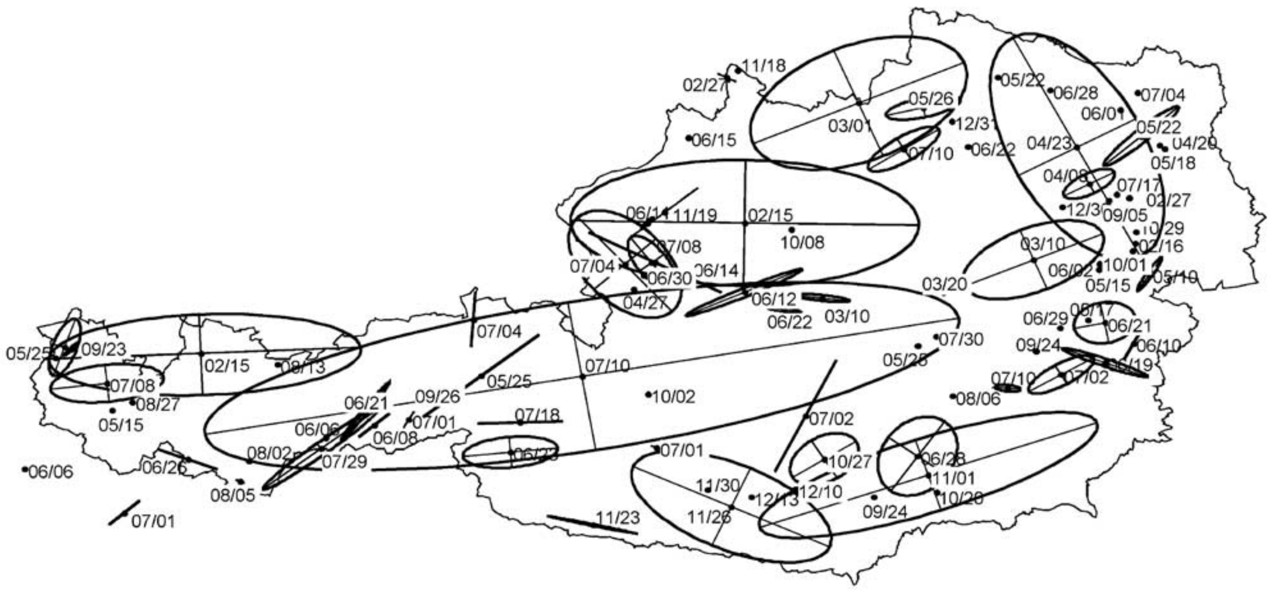


**Figure 4.** Spatial coherence of all maximum annual floods of 1990 in Austria. Numbers at the centers of the ellipses indicate month/day of the flood events.

occurring on the same (or following) day in catchments that are close to each other are the result of the same event we also assigned the same flood process type to all of these annual floods. This means that each cluster of the coherency analysis is associated with one process type. Our database consisted of a total of 11518 observed maximum annual flood peaks in 490 Austrian catchments for the years 1971–1997. On the basis of the coherency clustering, these peaks resulted in 2266 flood events, which were then classified.

[28] The main tool we used in the classification procedure was diagnostic maps. The maps covered all of Austria. For each flood event, the maps contained the information of all indicators in a way 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 different flood indicators. Figure 5 presents three examples of the diagnostic maps. For clarity, not all the indicator layers are shown, and again for clarity, we focus on a small part of Austria. The location of the detailed maps (red rectangles) and the spatial coverage of the flood event (black catchment boundaries) on these particular days are shown in the inset maps in the lower left corners. Each catchment has been colored by hues from red to green representing low to high runoff coefficients on this particular day. For nested catchments, the values of smaller catchments have been plotted on top of those of larger catchments. Catchments in which a maximum annual flood peak occurred on this day have been cross-hatched. 1-day rainfall is represented by blue circles with open circles indicating low rainfall depths, half-full circles indicating medium rainfall depths, and full circles indicating large rainfall depths. 3-day rainfall is represented by open black circles, with the size indirectly proportional to rainfall depth. Snowmelt, $P_m$, and snow water equivalent, *SWE*, are represented by a red letter M and a black snow crystal, respectively, with the size of the symbols being proportional to the values of the indicators. Time of concentration, $tc^*$, is represented by a red letter C, with the size inversely proportional to $tc^*$. This means that flashy response corresponds to large letters C. The duration of extreme storms is represented by a red flash symbol. All symbols have been plotted around the catchment centroids.

[29] Figure 5 (top) shows the hydrological situation on 7 July 1997. The spatial extent of the flood was large as, on this day, the maximum annual flood occurred in nearly all the catchments at the northern fringe of the Alps. Large daily rainfall depths were measured in the entire region. The runoff coefficients in most catchments where the annual flood occurred were close to unity due to substantial antecedent rainfall. The runoff response dynamics in the catchments ranged from fast to medium and there were substantial differences between the catchments. All the catchments were snow free and no extreme rainfalls of short duration were observed. We therefore classified this flood event as a long-rain flood.

[30] Figure 5 (middle) shows the situation on 12 July 1978. The spatial extent of the flood was very small as, on this day, the maximum annual flood occurred in only two small neighboring catchments. The observed daily rainfall depths were rather small and antecedent rainfall was minimum. However, a high intensity rainfall burst of 90 min duration occurred. The runoff coefficients were estimated to about 0.5, i.e., relatively dry catchment conditions, and the times of concentration were short. We therefore classified this flood event as a flash flood.

[31] Figure 5 (bottom) shows the situation on 24 December 1995. Most of the catchments were snow covered and substantial snowmelt occurred. Rainfall also occurred although the rainfall depths were rather low. The runoff coefficients ranged from medium to high values and the runoff response dynamics were rather fast. We therefore classified this flood event as a rain-on-snow event.

[32] The diagnostic maps also allowed us to assess the assumption of all catchments constituting one event (i.e., one cluster) to be associated with the same flood process

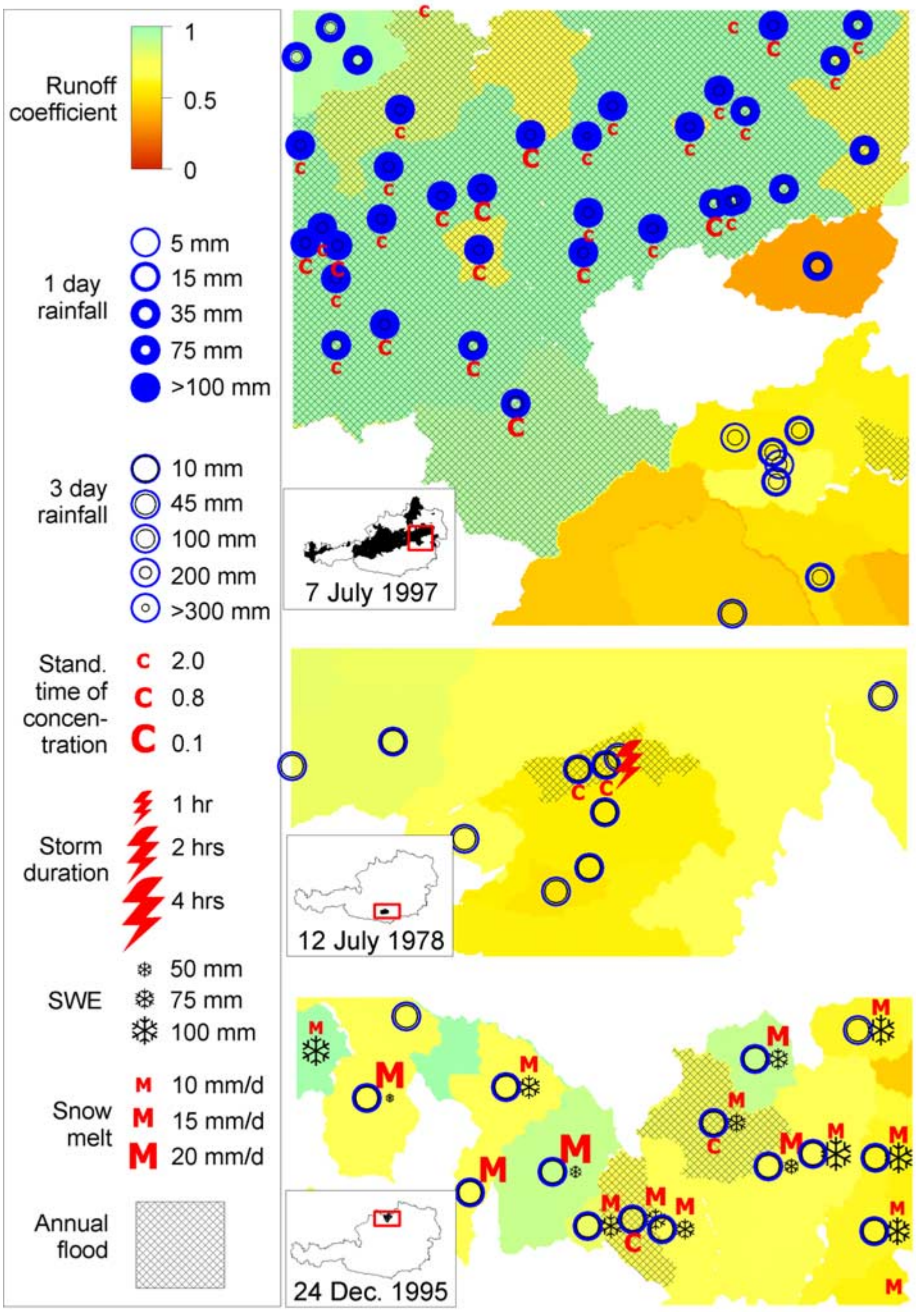


**Figure 5.** Diagnostic maps for classifying maximum annual floods according to process type. Examples of three process types are shown: (top) long-rain flood, (middle) flash flood, and (bottom) rain-on-snow flood. All symbols have been plotted around the catchment centroids.

types. In the vast majority of the cases this assumption was valid. In a number of instances, in large clusters, rainfall floods occurred in the lowland catchments, while in the higher altitude catchments snow processes were involved in addition to rainfall. We treated the flood peaks of the entire cluster either as long-rain floods or as rain-on-snow floods, depending on which of the processes prevailed in the cluster. Another borderline case was where small-scale short-duration convective events were imbedded in larger-scale synoptic rain fields. In these events, the majority of the catchments was always of the long-rain type. We therefore treated the flood peaks of the entire cluster as long-rain floods.

[33] To illustrate the plausibility of the classification into flood process types we compared a number of events with more detailed descriptions reported in the literature. Most of the published case studies of floods in Austria relate to major floods that produced significant damage. The flood event on 7 July 1997 (top panel of Figure 4) has been analyzed in detail by *Hydrographischer Dienst Österreich* [1998]. In early July, lows in upper Italy and the Slovak Republic associated with an upper air trough steered warm

**Table 2.** Results of the Flood Type Classification of Maximum Annual Floods in 490 Austrian Catchments, 1971–1997

| Process Type[a] | 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 < 10yr flood | 2051 (41.3%) | 1541 (47.8%) | 225 (41.3%) | 957 (39.3%) | 94 (27.1%) | 4868 (42.3%) |
| Number of flood peaks > 10 yr 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%) |

[a]MAF is the mean annual flood.

unstable air north-eastward to Northern Austria and the Carpathians. Persistent rainfall occurred in the entire Northern Alps from 4 July until the evening of 6 July. Event rainfall totaled at least around 100 mm, up to 300 mm in the east, and 400 mm in the Carpathians. The spatial pattern of rainfall clearly indicates orographic enhancement effects. The return periods of the floods produced in the catchments of this region range between 2 years in the west and more than 100 years in the east. This event has been classified as a long-rain flood by the procedure proposed here which is a correct classification in the light of the more detailed information. Similarly, the flood on 10 July 1990 shown in Figure 4 was classified as a long-rain flood.

[34] On 1 August 1992 an extreme flood occurred in Tyrol at the Austrian-German border [*Gutknecht and Watzinger*, 1999]. In the 55 $km^2$ Dürrach catchment the observed peak flow was 262 $m^3/s$ which is about three times the second largest flood peak on record. The five day antecedent rainfall at a station in the catchment was 33 mm, the event rainfall was 61 mm. The storm duration was 3 hours, and the maximum intensity was 23 mm in 15 min. This storm produced a very fast runoff response. On 31 July and 1 August, rainfall depths ranged between 40 and 100 mm at five rain gauges within a radius of less than 25 km, but rainfall stations further apart had insignificant rainfall. Here, this event has been classified as a short-rain flood which, again, is appropriate.

[35] Another example is the flood of 23 December 1991 of the Salzach at Salzburg [*Blöschl et al.*, 2000b]. The observed flood peak of 1376 $m^3/s$ in this 4426 $km^2$ catchment was estimated as a 7 year flood. Elevations in the catchment range from 400 to more than 3000 m. On 16 December there was some snowfall in the entire region, on 18 and 19 December air temperatures increased and there was some rainfall. On 20 December air temperatures dropped to temperatures well below freezing in the entire region and heavy snowfalls occurred. These produced snowpacks of about 50 mm snow water equivalent in the lower parts of the catchment, and in the upper parts existing snowpacks were increased from about 150 mm to about 250 mm. On 21 December air temperatures increased and heavy rainfalls occurred. On the following day, temperatures increased dramatically while there was little precipitation. On 23 December the was some rainfall and some melt. This event has been classified as a rain-on-snow event by the procedure proposed in this paper.

## 6. Results

### 6.1. Classification Results of Flood Magnitudes

[36] The classification of the 2266 flood events of the years 1971 to 1997 resulted in the following break up: 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 (Table 2). This means that almost two thirds of the flood events were long-rain and short-rain floods. The break up of the events allowed us to assign a process type to each flood peak which resulted in the following break up of the 11518 maximum annual flood peaks classified in the 490 Austrian catchments. 4966 (43%) long-rain floods, 3225 (28%) short-rain floods, 545 (5%) flash floods, 2435 (21%) rain-on-snow floods and 347 (3%) snowmelt floods (Table 2). This means that, as we move from events to flood peaks, the frequency of the long-rain process type increases significantly while the frequency of the flash flood process type decreases significantly. This is related to the number of peaks per event. The long-rain floods are usually large-scale events covering a large number of catchments and hence a large number of maximum annual flood peak values. In contrast, flash floods are usually small-scale events covering only one or two catchments so the number of observed maximum annual flood peaks is much lower than in the case of long-rain floods. Because of this, the long-rain flood type is the most common type in Austria based on a comparison of maximum annual floods.

[37] As the processes involved in each of the flood types are quite different one would expect that the relative frequency of the process types changes with the magnitude of the event. Figure 6 shows two examples of flood frequency curves of the catchments analyzed. The symbols indicate the flood process types. Figure 6a relates to the Fahrafeld catchment (186 $km^2$ catchment area) in the eastern most part of the Alps near Vienna. Out of the 26 maximum annual flood peaks observed, 14 flood peaks were associated with long-rain floods, 3 with short-rain, 8 with rain-on-snow and 1 with snowmelt. Figure 6b shows the flood frequency curve for the Obermühl catchment (199 $km^2$ 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 meltwater 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 the

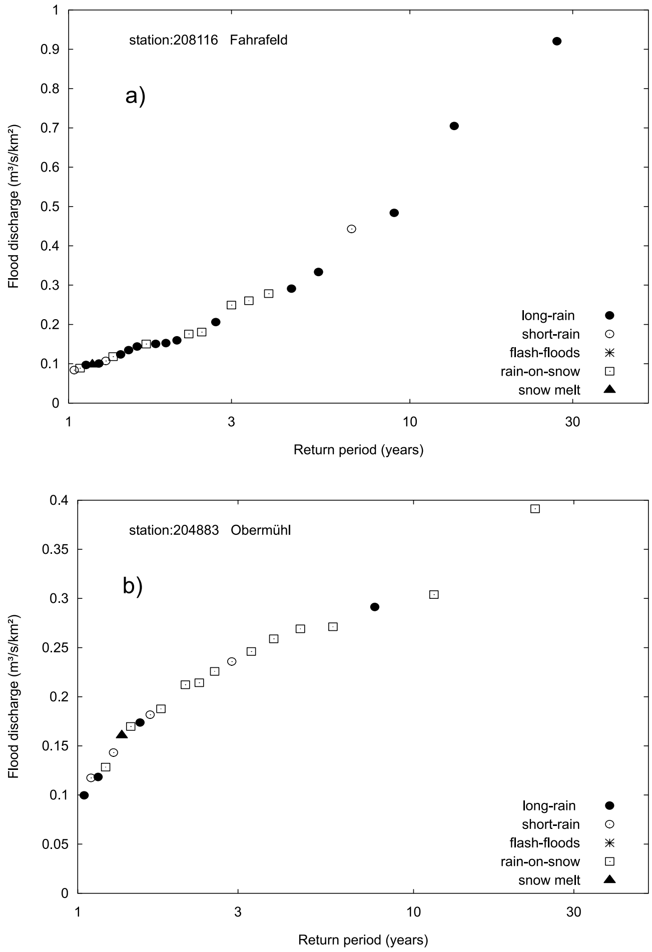


**Figure 6.** Flood frequency plots with the process types indicated. (a) Triesting at Fahrafeld, 186 $km^2$ catchment area; (b) Kleine Mühl at Obermühl, 199 $km^2$ catchment area.

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 in these two catchments.

[38] In Table 2 we have examined, for all 490 catchments, whether the relative frequency of the process types changes with the magnitude of the event. 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 snowmelt 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 meltwater release.

## 6.2. Regional Patterns of Process Types

[39] Figures 7a–7e shows the spatial patterns of the frequency of long-rain floods, short-rain floods, flash floods, rain-on-snow floods and snowmelt floods in Austria. This frequency is the number of years a maximum annual flood is classified as a certain process type, scaled by the total number of years for each catchment. Figure 7a indicates that long-rain floods are the main causative process type of annual maximum floods in most catchments in Austria, as the frequencies are on the order of 0.5 (see Table 2). In catchments at the northern fringe of the high Alps, long-rain floods are particularly common. The high Alps tend to act as a topographic barrier to north-westerly airflows, and orographic enhancement often produces persistent rainfall which can result in floods. The regions of the highest relative importance of long-rain floods are identical with the regions of the highest mean annual rainfall in Austria. Short-rain floods (Figure 7b) also occur quite commonly with a frequency on the order of 0.3. There are, again, significant spatial differences. Short-rain floods occur more frequently in southern Austria than north of the Alps. This is likely due to two mechanisms. The main ridge of the Alps tends to block weather systems approaching from the northwest which reduces the advection of moist air and hence the persistence of the rainfall. Also, south of the Alps southern airflows may produce floods that are associated with high-intensity short-duration storms. There is likely a tendency for a quicker response of some of the catchments south of the main Alpine ridge as compared to the north of it (Figure 3) which tends to enhance the role of short duration storms in flood generation. Flash floods occur significantly less frequently (Figure 7c) than long-rain and short-rain floods. Flash floods are only important in eastern Austria, specifically in the hilly region of Styria in south-eastern Austria and in the hilly region of Waldviertel in north-eastern Austria. The hilly terrain appears to increase the instability of the boundary layer and hence the likelihood of convective storms. Throughout Austria, the spatial pattern in Figure 7c is rather patchy which reflects the random and local nature of flash floods causing maximum annual floods. Rain-on-snow floods (Figure 7d) are important in the catchments of medium altitude in the north of Austria. A rapid increase in air temperature in early winter or spring appears to occur quite frequently as a result of the inflow of warm and moist air. Relatively low rainfall depths on an existing snow cover appear to produce a significant portion of maximum annual floods in these catchments. Snowmelt floods (Figure 7e) rarely produce the maximum annual flood. Those catchments with frequencies of snowmelt floods of more than 0.1 are mainly located in the high Alps where both snow and glacier melt can be important for flooding, and in northern Austria where early spring snowmelt may produce floods. However, as indicated above, these are usually minor floods.

## 6.3. Process Types and Event Properties

[40] To examine the event characteristics we analyzed all observed maximum annual flood peaks in all catchments as a function of the sum of 3-day rainfall and snowmelt which is a measure of the water available for flood generation. For clarity we calculated the quantiles of the flood peaks for classes of 3-day rainfall and snowmelt and plotted the 5%, 10%, 50%, 90% and 95% quantiles of each class against the mean of 3-day rainfall and snowmelt in each class in Figure 8. In Figure 8a the quantiles of all peaks have been plotted, in Figures 8b–8f we stratified the flood peaks by the process type. The maximum 3-day rainfall plus snowmelt inputs of the long-rain and short-rain floods are larger

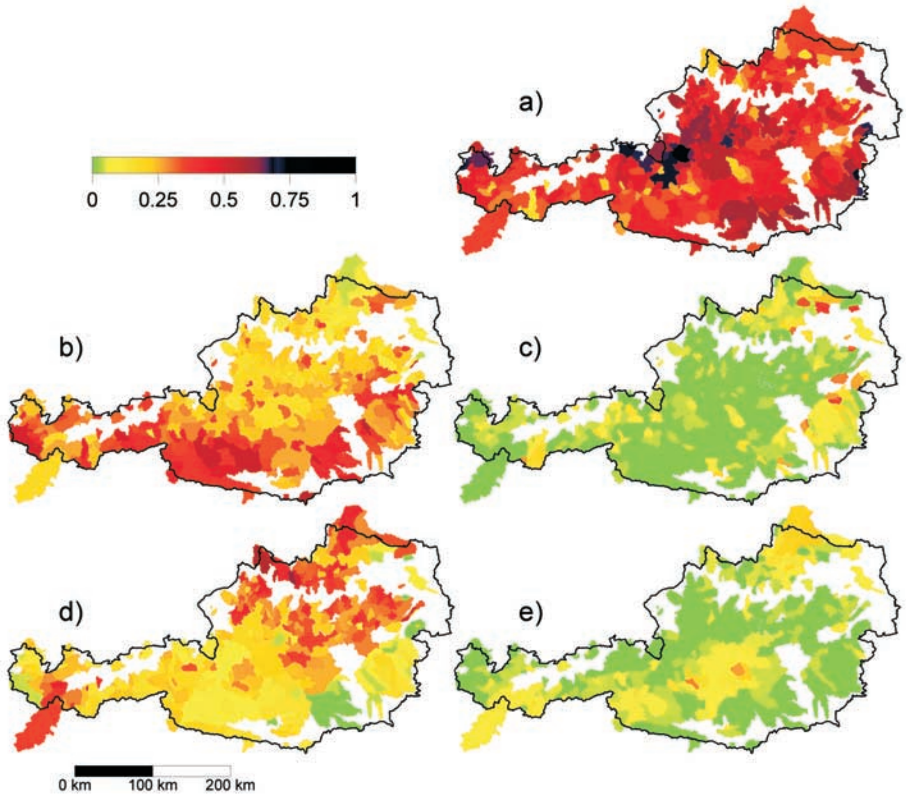


**Figure 7.** Regional patterns of the frequency of flood process types. A frequency of unity indicates that in a catchment all the maximum annual floods are due to one particular process while a frequency of zero indicates that this process never leads to a maximum annual flood. (a) Long-rain floods, (b) short-rain floods, (c) flash floods, (d) rain-on-snow floods, and (e) snowmelt floods. For nested catchments the frequencies of the smaller catchments have been plotted on top of those of the larger catchments, and only catchments smaller than 5000 $km^2$ are shown.

than those of the flash floods, rain-on-snow and snowmelt floods, so the quantiles of the former extend further to the right in Figure 8. Figure 8 indicates that for long-rain and short-rain floods the flood peaks tend to increase with increasing rainfall and snowmelt. The relationship is curvilinear with small rainfall depths producing small flood discharges, and as about 30 mm of rainfall and melt are exceeded, the relationship gets progressively steeper, i.e., the floods are progressively larger. The intercept of, say, 30 mm can be interpreted as a loss in runoff generation, and the curvilinear shape reflects the non-linearity of runoff generation with increasing event rainfall depth. For rain-on-snow floods (Figure 8e) there is also an increase of the flood peaks with rainfall input although the increase is less steep. For the flash floods the flood peak discharges seem to be less dependent of the rainfall input. The scatter is larger which means that, for a given rainfall plus melt flood, peaks can vary over a wider range than for the other process types. Apparently, for the flash flood process type, rainfall depth is not the main control of the peak discharge. It is likely that rainfall intensity is a much more important control. For the snowmelt process type (Figure 8f) the flood peaks are always small, as discussed above. They are essentially not related to the rainfall and snowmelt input. As fair weather snowmelt situations usually last over a period of one to two weeks it is likely that the antecedent soil moisture, as controlled by weekly or bi-weekly snowmelt, is a much more important control for flood peaks than is the 3-day snowmelt.

[41] In Figure 9 we analyzed the daily runoff coefficient, as calculated by the model, against the sum of 1-day rainfall and snowmelt in a similar fashion as in Figure 8. Figure 9a shows all data, and Figures 9b–9f show the data stratified by the process type. For long-rain floods, short-rain floods and rain-on-snow floods there is a clear tendency for the runoff coefficients to increase with the sum of rainfall and snowmelt. The median of the runoff coefficients increases from about 0.2 to 0.9 with the sum of 1-day rainfall and snowmelt increasing from 2 to 100 mm. For larger rainfall and snowmelt inputs the runoff coefficients are never small. The runoff coefficients of the flash floods exhibit a less pronounced dependence on the water input and the scatter is much larger. The runoff coefficients are almost uniformly distributed over the entire possible range. As suggested above, it is not the rainfall depth but rainfall intensity that likely controls the magnitude of the flood peaks for this type. It should also be noted that the runoff coefficients shown here are rather high as compared to event runoff coefficients reported in literature [see, e.g., *Pilgrim and Cordery*, 1993, p. 9.17]. The runoff coefficients used here have been derived from the daily runoff components of the water balance simulations and so are not directly comparable with event-scale values. However, we would assume that trends similar to those in Figure 9 would also appear in

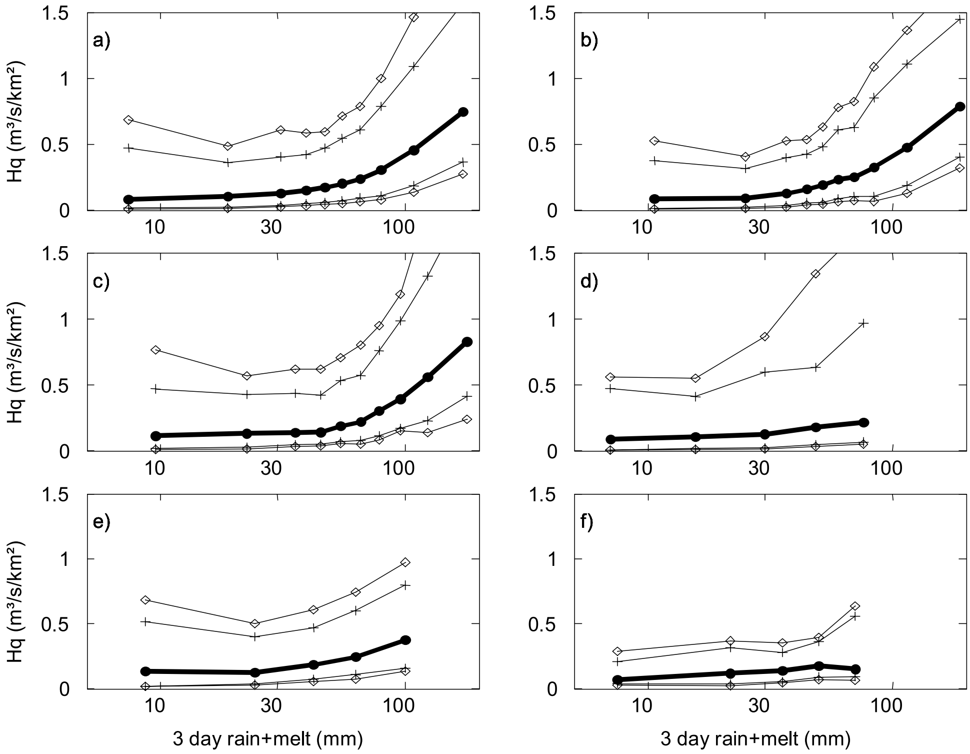


**Figure 8.** Quantiles of specific flood peaks of maximum annual floods plotted versus 3-day rainfall plus melt. (a) All flood types, (b) long-rain floods, (c) short-rain floods, (d) flash floods, (e) rain-on-snow floods, and (f) snowmelt floods. Diamonds represent 5% and 95% quantiles, crosses represent 10% and 90% quantiles, and thick lines with disks represent the 50% quantiles.

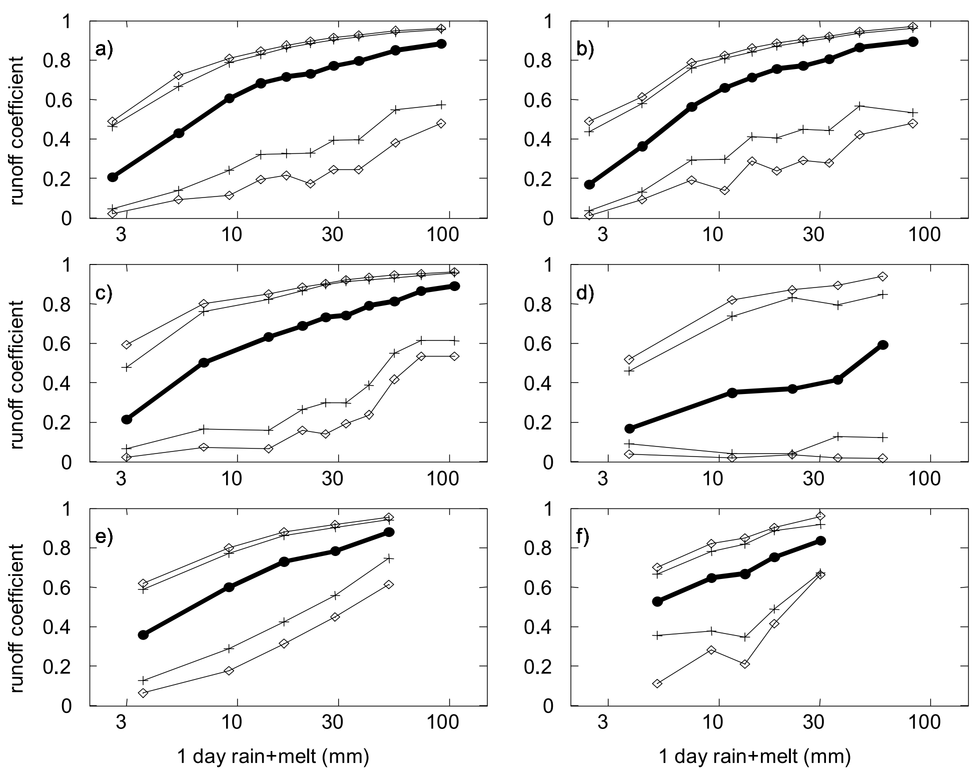


**Figure 9.** Quantiles of runoff coefficients (equation (1)) associated with maximum annual floods plotted versus 1-day rainfall plus melt. (a) All flood types, (b) long-rain floods, (c) short-rain floods, (d) flash floods, (e) rain-on-snow floods, and (f) snowmelt floods. Diamonds represent 5% and 95% quantiles, crosses represent 10% and 90% quantiles, and thick lines with disks represent the 50% quantiles.

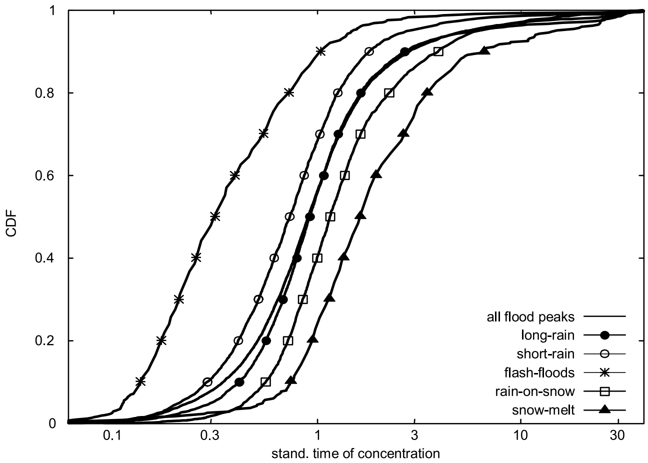


**Figure 10.** Cumulative distribution function of the standardized times of concentration *tc** according to equation (4) for all maximum annual flood peaks, stratified by process type.

an analysis of event runoff coefficients albeit with lower values.

[42] To examine the runoff dynamics, in addition to runoff generation, in Figure 10 the cumulative distribution function of the standardized times of concentration *tc** according to equation (4) has been plotted for all maximum annual flood peaks, stratified by process type. All process types exhibit a significant scatter of the times of concentration which is more than two orders of magnitude. It is likely that this scatter is a result of enormous differences in the catchment characteristics. The average values of the times of concentration do differ between the process types. Flash floods exhibit, on average, the shortest times of concentration as would be expected. The median of *tc** is about 0.3. This is likely due to two reasons. The first is the presence of flashy catchment characteristics which increases the likelihood of short high-intensity storms to produce the maximum annual flood. The second reason is partial coverage of catchments by local storms which again produces flashy runoff responses and hence short times of concentration. The largest times of concentration are produced by the snowmelt flood type with the median of *tc** of about 2. Snowmelt floods usually occur during extended snowmelt spells, so the peaks do not tend to be very flashy.

### 6.4. Process Types and Seasonality

[43] In Figure 11 the flood peaks have been plotted against the day of occurrence within the year, stratified by the process type. Long-rain floods occur throughout the year but there is a tendency for more events and more extreme events to occur in summer, particularly in June and July. This is because heavy rainfall events occur more frequently in the summer months than in the rest of the year. Short-rain floods also mainly occur in the summer and there is a tendency for some of the major events to also

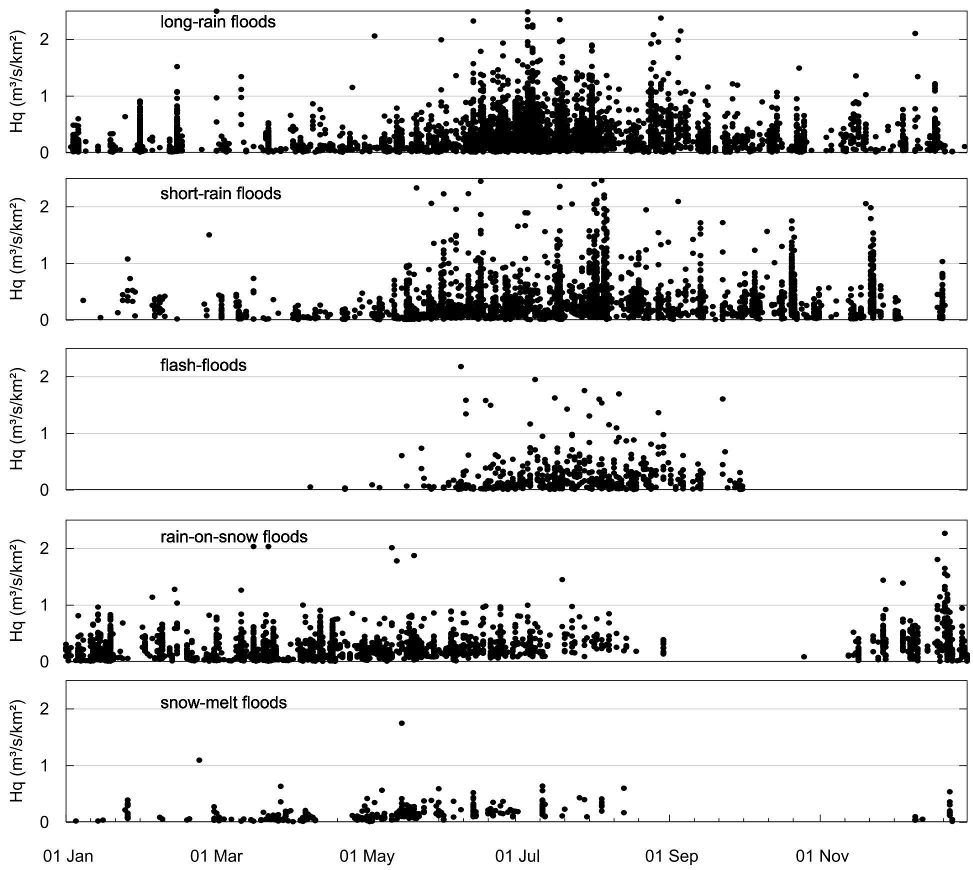


**Figure 11.** Specific flood peaks of maximum annual floods plotted versus the date of occurrence within the year, stratified by process type.

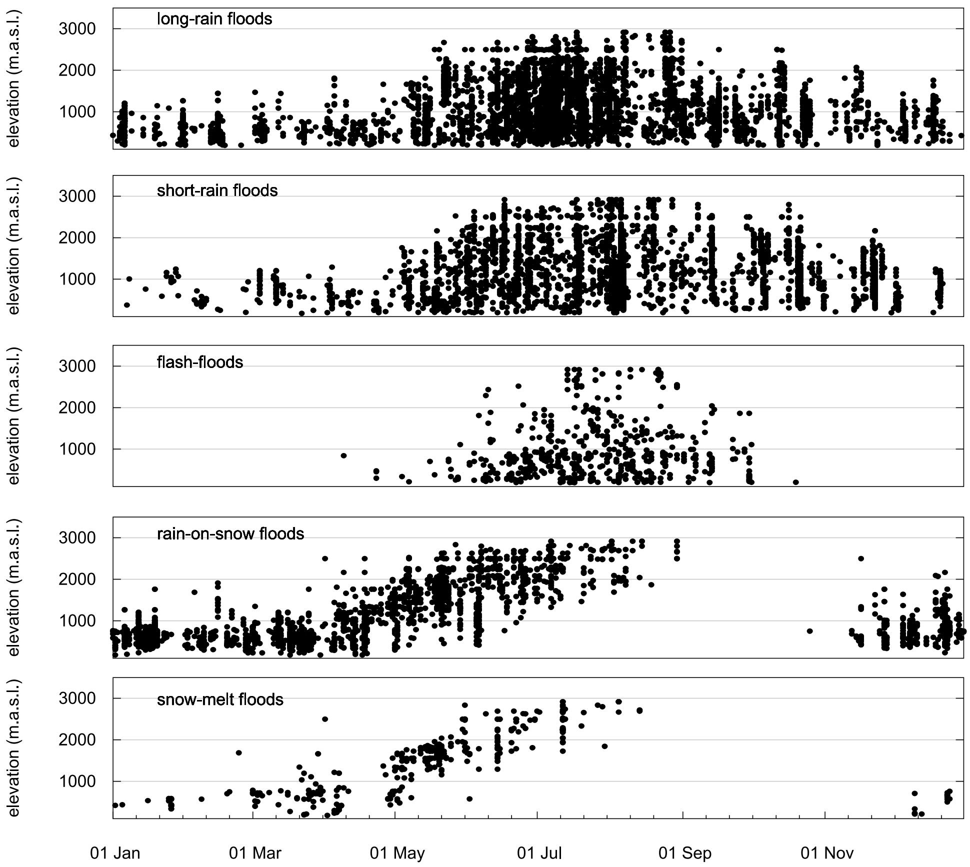


**Figure 12.** Average catchment elevation plotted versus the date of occurrence of the maximum annual flood, stratified by process type.

occur in autumn. These are events that have occurred in southern Austria (Figure 7b). Flash floods only occur in summer when enough energy is available for convective storms. Rain-on-snow floods occur throughout the year with the exception of late summer and early autumn. The largest rain-on-snow floods occur in late December. Similarly, snowmelt floods occur throughout the year with the exception of late summer and autumn when all of the catchments are snow free.

[44] The seasonal pattern in the flood occurrence is mainly related to the annual fluctuations in air temperature. Air temperature also exhibits a strong altitudinal dependence. In Figure 12 the mean elevation of each catchment has therefore been plotted versus the day of occurrence of the maximum annual flood. Figure 12 shows very pronounced seasonal patterns for all flood types. Long-rain floods and short-rain floods exhibit an upper envelope of about 1000 m asl from January to April. In late spring and summer these flood types can occur in catchments of any elevation. At the end of the year the upper envelope gradually decreases to 1000 m asl. This pattern of the upper envelope closely follows the snow fall line. In the high altitude catchments no maximum annual floods occur in the cold months of the year as most of the precipitation falls as snow. Flash floods exhibit a strong seasonal pattern following the annual pattern of global radiation. It is interesting that, in July and August, flash floods can occur in catchments with elevations of up to 3000 m asl. These are likely a result of convective storms that can occur at any altitude during summer. Rain-on-snow floods and snowmelt floods exhibit a narrow altitudinal range of occurrence which varies with time of the year. In winter both types occur in catchments lower than 1000 m asl The altitudinal range gradually increases during spring and extends from 2000 to 3000 m asl in summer. This pattern is clearly related to the seasonal pattern of air temperature. 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.

### 6.5. Process Types and Flood Sample Characteristics

[45] To provide insight into the statistical characteristics of the flood peaks for each of the process types we calculated the mean annual floods (MAF) and the coefficients of variation (CV). To calculate the stratified MAF the record of maximum annual floods of each catchment has been split into five parts, according to process type, and the mean of each part has been calculated separately. Because of this, the sample size for calculating the mean is much smaller than for the unstratified case and for some catchments certain flood process types never occur. The mean values used here relate to those samples with at least two values. Table 3 gives the average values of the MAF for each process type. The short-rain floods exhibit, on average, the largest MAF, and the long-rain floods exhibit slightly smaller values. The snowmelt floods exhibit, on average, the smallest MAF. This is consistent with the previous analyses in this paper.

**Table 3.** Averages of Mean Annual Floods (MAF) and Coefficients of Variation (CV) of Annual Floods For Each Process Type[a]

| Process Type | Long-Rain Floods | Short-Rain Floods | Flash Floods | Rain-on-Snow Floods | Snowmelt Floods | All Types |
|---|---|---|---|---|---|---|
| Average (MAF) | 0.343 | 0.407 | 0.271 | 0.293 | 0.156 | 0.331 |
| $a$ | 1.377 | 1.462 | 1.863 | 1.057 | 0.517 | 1.342 |
| $b$ | −0.303 | −0.285 | −0.413 | −0.274 | −0.205 | −0.298 |
| Average (CV) | 0.494 | 0.456 | 0.457 | 0.338 | 0.268 | 0.516 |
| $c$ | 0.660 | 0.554 | 0.301 | 0.448 | 0.343 | 0.697 |
| $d$ | −0.061 | −0.042 | 0.089 | −0.059 | −0.043 | −0.065 |

[a]Here $a$, $b$, $c$, and $d$ are the regression coefficients of MAF ($m^3/(s\ km^2)$) and CV with catchment area $A$ ($km^2$) in MAF = $aA^b$, CV = $cA^d$. Included are 490 Austrian catchments, 1971–1997.

[46] It is now of interest to relate the MAF to catchment area. In Figure 13a the specific mean annual floods, MAF, of all process types have been plotted against catchment area. Figures 13b–13f show the specific mean annual floods stratified by process type. To assist in the analysis of the trend of the MAF with catchment area, we fitted a power law

$$\mathrm{MAF} = aA^b \tag{5}$$

to the data by ordinary least squares, where $A$ is catchment area. The regression coefficients $a$ and $b$ are given in Table 3. Figure 13 indicates that for all process types the specific mean annual floods tend to decrease with catchment area but there are significant differences between the process types. For long rain-floods, short-rain floods and rain-on-snow floods the exponent of the fitted power law is in a medium range (−0.303, −0.285 and −0.274, respectively). For flash floods (Figure 13d) the MAF decrease more quickly with catchment area and the exponent of the fitted line is $b = -0.413$ (Table 3). The interpretation of this result is the fairly limited spatial extent of convective storms. For snowmelt floods, however, the MAF decrease more slowly with catchment area than for the other process types and the exponent is $b = -0.205$ (Table 3). The interpretation of this result is that snowmelt floods are never very large irrespective of catchment area because of the upper limit of energy available for meltwater release. Also, it is likely that

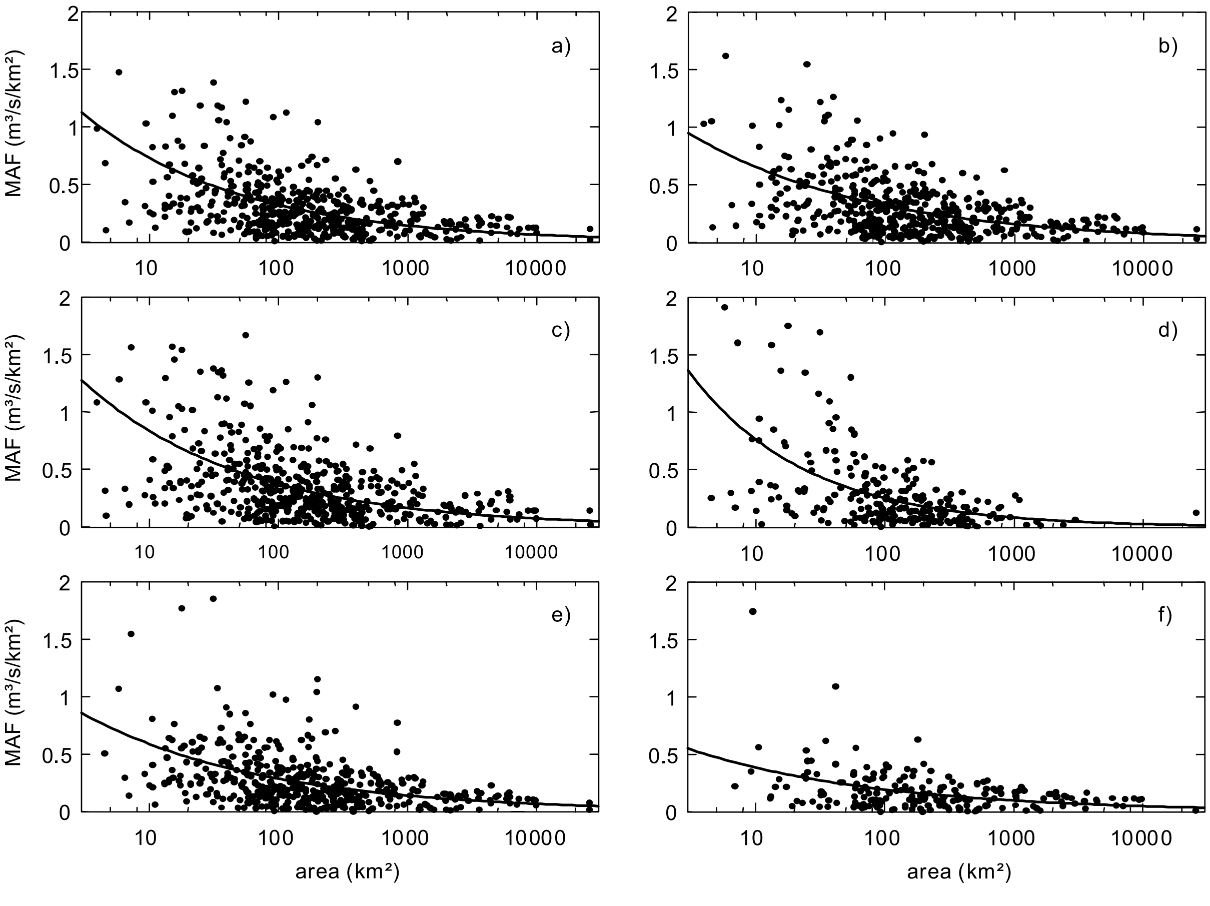


**Figure 13.** Mean of specific annual floods stratified by process type and plotted versus catchment area. (a) All flood types, (b) long-rain floods, (c) short-rain floods, (d) flash floods, (e) rain-on-snow floods, and (f) snowmelt floods. A regression line is shown.

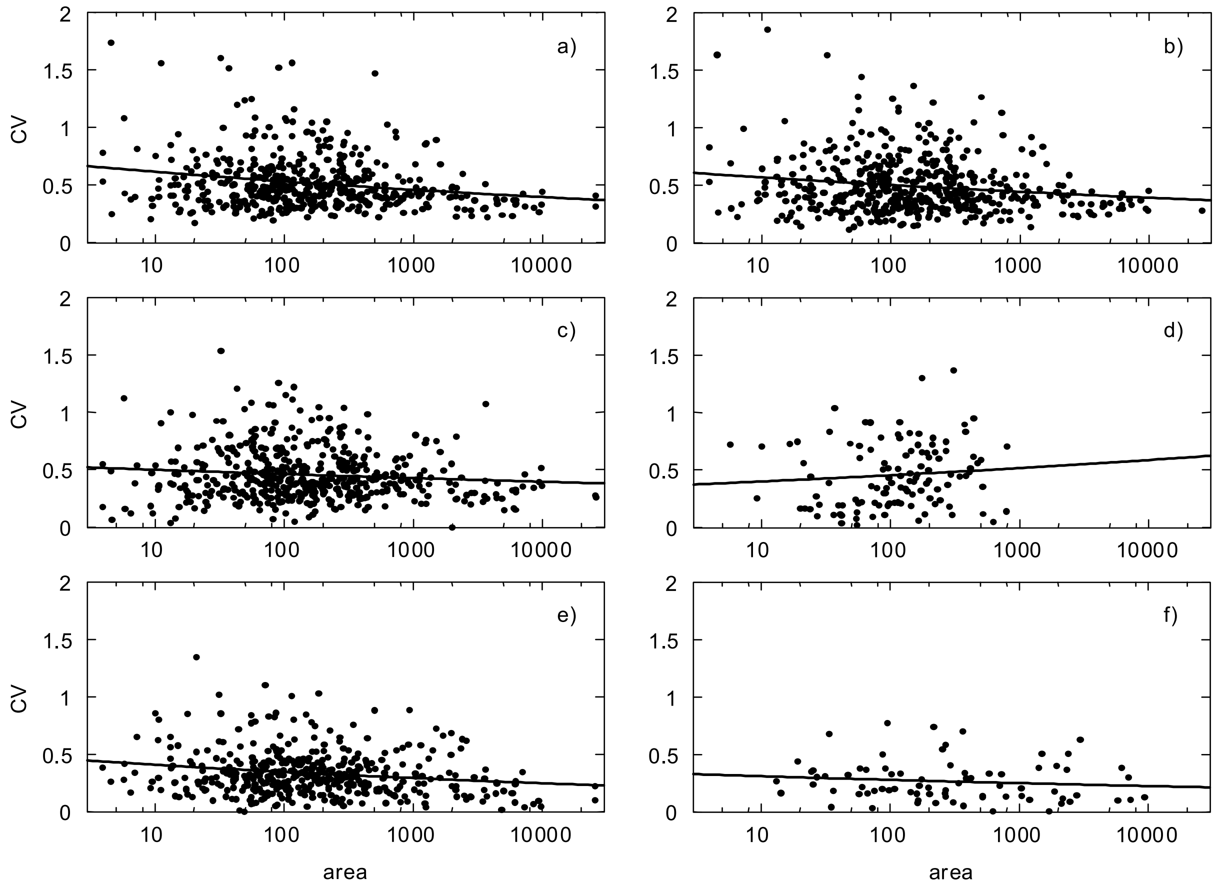


**Figure 14.** Coefficient of variation of specific annual floods stratified by process type and plotted versus catchment area. (a) All flood types, (b) long-rain floods, (c) short-rain floods, (d) flash floods, (e) rain-on-snow floods, and (f) snowmelt floods. A regression line is shown.

snowmelt floods are spatially more uniform than other types of floods which would, again, translate into relatively moderate decreases of the MAF with catchment area.

[47] The stratified CVs have been calculated in a similar way as the MAF but only those samples with at least three values have been used. The average values of the CV for each process type are given in Table 3. The long–rain floods exhibit, on average, the largest CV, but those of short-rain floods and flash floods are only a little smaller. The snowmelt floods exhibit, on average, the smallest CV, and the CVs of rain-on-snow floods are also small. Clearly, meltwater release is a process that is not as variable as rainfall.

[48] In Figure 14 the CV of the maximum annual flood samples have been plotted against catchment area, both for the entire data set (Figure 14a) and the stratified data sets (Figures 14b–14f). The regression coefficients *c* and *d* with catchment area are given in Table 3. Figure 14 indicates that for most process types the coefficient of variation decreases with catchment area, and the *d* exponents are on the order of −0.05 (Table 3). The CVs of long-rain floods decrease slightly more quickly with catchment area than those of the short-rain floods and the snowmelt floods although the difference is small. The exception are the flash floods as for this process type the CV increases with catchment area and the *d* exponent is 0.089. The catchment range is only two orders of magnitude, so the trend with area is not as well defined as for the other processes, but it is clear that the CVs do increase with catchment area for this process type.

## 7. Discussion and Conclusions

[49] 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, in most cases, it was 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 hydrologic reasoning and they are consistent with experience in the study region. For example, the flood event of 7 July 1997 shown in Figure 5 has been identified as a large-scale synoptic event in a detailed study of *Hydrographischer Dienst Österreich* [1998].

[50] The strength of the approach proposed in this paper is that it is applicable to 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. We classified 11,518 flood peaks which is certainly a number that makes the approach appealing to regional flood frequency studies. Another important char-

acteristic of the proposed approach is that it is viable in the presence of incomplete data. If, say, hourly data were available for all stream gauges and for all rain gauges 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. These indicators have been 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. For example, as compared to the seasonality analysis of Figure 1, Figures 11 and 12 clearly provide a more comprehensive assessment of flood processes. Using seasonality alone, one can distinguish between some of the processes, such as flash floods and snowmelt. However, one cannot distinguish between process types that exhibit similar seasonal patterns such as long-rain floods and short-rain floods, or rain-on-snow floods and snowmelt floods.

[51] There are examples, where different process indicators provide complementary information on the same process which increases the robustness of the classification. For example, in south-eastern Austria the seasonality analysis highlights the importance of summer storms, the times of concentration are short, the durations of observed storms causing floods are short and the analysis of the spatial flood coherence indicates that most floods are local flood events. This provides ample evidence for the role of convective storms in flood generation in this particular region.

[52] 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 to actually produce a major flood significant rainfall depths are needed [*Merz et al.*, 1999a]. 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 durations (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, usually, are not very extreme, and relatively dry catchment conditions in summer when these types of events occur. It should also be noted that the gauged catchments analyzed in this paper are not very small, with the median catchment area of about 150 $km^2$. If smaller catchments were analyzed it is likely that the frequency of flash floods would be significantly higher. Rain-on-snow is an important causative mechanism, similar to south-eastern Germany [*Sui and Koehler*, 2001]. Floods that are due to snowmelt alone are the least frequent process type producing maximum annual floods.

[53] 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 we used, but only 5 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 meltwater release.

[54] We found pronounced spatial patterns in the frequency of flood type occurrence. Long-rain floods are of major importance in the region of orographic rainfall enhancement at the northern fringe of the high Alps. Short-rain floods occur more frequently in southern Austria than north of the Alps. This is likely due to two mechanisms. The main ridge of the Alps tends to block weather systems approaching from the northwest which reduces the advection of moist air and hence the persistence of the rainfall. Also, south of the Alps southern airflows may produce floods that are associated with high-intensity short-duration storms. Flash floods due to short convective storms are common in the hilly region in south-eastern Austria and, more locally, in a few catchments in the Alpine areas and in northern Austria. The regional patterns of the long-rain flood and the flash flood frequencies are very similar to patterns of extreme orographic and convective rainfall, respectively, obtained by *Haiden and Kahlig* [1994] in a simulation study using an atmospheric mesoscale model in Austria. This similarity corroborates the interpretation of the flood types in this paper. Rain-on-snow floods most commonly occur in northern Austria. This region is very close to the catchments of *Sui and Koehler* [2001] in the Bavarian forest who found that 70% of the top 10 peak discharges in 17 catchments were rain-on-snow events. In this study we found that, in this region, up to 55% of all maximum annual floods were due to rain on snow.

[55] The different process types exhibit different event properties. Runoff coefficients tend to increase with rainfall depth for long-rain floods. This increase is reminiscent of the characteristics of runoff generation by the saturation excess mechanism which is likely to be operative in parts of the catchment. Runoff coefficients are less dependent of rainfall depth and exhibit much larger scatter for flash floods. Apparently, for this process type rainfall depth is not the main control of peak discharge. It is likely that rainfall intensity is the more important control. One would expect the infiltration excess mechanism in parts of the catchment to produce these characteristics. The runoff dynamics of the catchments also differ between the process types. Flash floods tend to exhibit the shortest times of concentration as would be expected. The largest times of concentrations are produced by the snowmelt flood type. Snowmelt floods usually occur during extended snowmelt spells, so the peaks do not tend to be very flashy.

[56] All process types exhibit seasonal patterns, both in terms of flood magnitudes and catchment altitudes of flood occurrence. These patterns are closely related to the annual patterns of air temperature and global radiation. Long-rain floods and short-rain floods occur throughout the year but in summer they are more frequent, can be of larger magnitudes 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 asl. Rain-on-snow floods and snowmelt floods exhibit a narrow altitudinal range of occurrence which varies with time of the year. In winter both types occur in catchments lower than 1000 m asl. The altitudinal range gradually increases during spring and

extends from 2000 to 3000 m asl 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. Rain-on-snow floods tend to be most extreme in late December. It is likely that these events are triggered by the advection of warm and moist air which produces significant energy input into the snow cover through condensation and long wave radiation. This is consistent with the notion of ''Christmas snowmelt flooding'' suggested by *Sui and Koehler* [2001] and well known by anecdotal evidence from locals in northern Austria and southern Germany.

[57] To examine the controls of the flood process types on the flood frequency characteristics the observed maximum annual flood samples were stratified according to process type. For all process types, the specific mean annual floods, MAF, tend to decrease with catchment area. For flash floods the MAF decrease more quickly with catchment area than for the other process types. The interpretation of this is the fairly limited spatial extent of convective storms. High rainfall intensities are only observed locally and hence the average rainfall drops more quickly with catchment area than is the case with larger-scale storms. This effect is illustrated by *Sivapalan and Blöschl* [1998] in the context of areal reduction factors of extreme storms for different spatial correlation structures. The rapid decrease is also consistent with the derived flood frequency simulations of *Blöschl and Sivapalan* [1997]. Their simulation results indicated that for their catchment regime IV (prealpine foothills and hilly terrain), the decrease of the specific mean annual flood with catchment area was the steepest of all catchment types. Prealpine foothills and hilly terrain are exactly those catchment locations of northern and south-eastern Austria where flash floods are the most important flood process type (Figure 7c). If one fits a power law to the simulation results of *Blöschl and Sivapalan* [1997, Figure 13-IV] the exponent is about $-0.4$ for all of the three model parameter sets they assumed. This is very close to the value of $-0.41$ obtained from the regression of the observed data in this paper (Table 3). The much smaller decrease of the MAF with catchment area for the snowmelt floods is also consistent with the more moderate decrease of the MAF in their runoff regime type III (snow dominated mountain streams). The exponents of a power law fitted to their simulations are about $-0.20$ to $-0.25$, depending on the parameter set used which again is close to the value of $b = -0.21$ found here. Overall, the simulations of *Blöschl and Sivapalan* [1997] are, however, about 50% higher than the regressions found in this paper, i.e., the *a* coefficients are about 1.5 of those found here (Table 3).

[58] The coefficient of variation of the flood samples stratified by process type decreases with catchment area for most process types. This is again consistent with the simulation results of *Blöschl and Sivapalan* [1997]. For their runoff regime type III (snow dominated mountain streams) the exponents of a power law fitted to the simulations are about $-0.035$ to $-0.045$, depending on the parameter set used which is similar to the value of $b = -0.043$ found here for the snowmelt flood type. However, overall, the simulated CV values of regime type III of *Blöschl and Sivapalan* [1997] are about twice those defined by the regressions in this paper, i.e., the *c* coefficients are about twice those found here (Table 3). There is one flood process type where the CV does not decrease with catchment area. This is the flash flood process type. The *d* exponent of the power law regression is 0.09. The catchment range is only two orders of magnitude, so the trend with area is not as well defined as for the other processes, but it is clear that the CVs do increase with catchment area for the flash flood process type. For two parameter sets of their catchment regime IV (prealpine foothills and hilly terrain), which corresponds to the flash flood type in this paper, the CV values simulated by *Blöschl and Sivapalan* [1997] remained approximately constant with catchment area, and for one parameter set (their set ''fast'') the CV increased with catchment area. *Blöschl and Sivapalan* [1997] attributed this increase to large nonlinearities in runoff generation associated with fast hillslope response times. This consistency with *Blöschl and Sivapalan* [1997] is encouraging as their approach was completely different from the one in this paper. Their approach was an upward approach in the terminology of *Klemeš* [1983] while the approach adopted in this paper is a downward approach. It is likely that the most efficient route to advancing our understanding of regional flood processes is a synthesis of the traditional upward or reductionist approach with the downward approach based on systematic learning from catchment response data [*Sivapalan et al.*, 2003].

[59] There exist a number of logical extensions of the work reported in this paper. We have adopted a catchment perspective, and it would 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* [1988] and *Lang and Grebner* [1998], for example. While only maximum annual floods have been available in this study, the analysis of partial duration series would provide a more complete picture of flood process types. Another possible extension we are planning is an attempt at automating the process classifications, based on prescribed rules, perhaps similar to the classification procedure of *Blöschl et al.* [2000b]. Ultimately, the flood process typology should be applied to improve the at-site and regional estimation of flood probabilities.

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