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Process controls on the statistical flood moments - a data based analysis

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Abstract:

In this paper, the controls of different indicators on the statistical moments (i.e. mean annual flood (*MAF*), coefficient of variation (*CV*) and skewness (*CS*)) of the maximum annual flood records of 459 Austrian catchments are analysed. The process controls are analysed in terms of the correlation of the flood moments within five hydrologically homogeneous regions to two different types of indicators. Indicators of the first type are static catchment attributes, which are associated with long-term observations such as mean annual precipitation, the base flow index, and the percentage of catchment area covered by a geological unit or soil type. Indicators of the second type are dynamic catchment attributes that are associated with the event scale. Indicators of this type used in the study are event runoff coefficients and antecedent rainfall. The results indicate that *MAF* and *CV* are strongly correlated with indicators characterising the hydro-climatic conditions of the catchments, such as mean annual precipitation, long-term evaporation and the base flow index. For the catchments analysed, the flood moments are not significantly correlated with static catchment attributes representing runoff generation, such as geology, soil types, land use and the SCS curve number. Indicators of runoff generation that do have significant predictive power for flood moments are dynamic catchment attributes such as the mean event runoff coefficients and mean antecedent rainfall. The correlation analysis indicates that flood runoff is, on average, more strongly controlled by the catchment moisture state than by event rainfall. Copyright © 2008 John Wiley & Sons, Ltd.

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INTRODUCTION

Understanding the process controls on the shape of the flood frequency curve is essential for reliably extrapolating at-site statistics to large return periods and for defining meaningful similarity indicators between catchments for flood frequency estimation in ungauged catchments. Analysis of the process controls on the shape of the flood frequency curve is usually done along two avenues, which one may term upward (or model based) approach and downward (or data based approach) (Klemeš, 1983). The idea of the upward approach, in the case of flood process analysis, 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 model and one hopes that the flood frequency curve so compiled reflects the composite behaviour of the underlying physical processes. The derived flood frequency approach was pioneered by Eagelson (1972) and applications of the approach are, amongst others, Fiorentino and Iacobellis (2001) and Sivapalan *et al*. (2005). The limitation of this approach is that it is not always clear how well the individual model components represent the interplay of the hydrological processes in the landscape. The alternative is the downward approach which starts directly at the scale of interest, i.e. the catchment scale by analysing observed flood runoff. The downward approach fingers 'down into the (smaller-scale) processes from above' (Sivapalan *et al*., 2003), by trying to understand what the mechanisms are that have led to observed flood behaviour. The difference in the upward approach is that the processes included in the analysis are not preconceived by the hydrologist's understanding of the hydrology of a catchment, but inferred from the data.

An example of the downward approach in flood process analysis is the classification approach, where flood peak samples are stratified in classes of flood types based on flood characteristics observed in the field. 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 (Gupta and Dawdy, 1995). However, often, the processes leading to flood runoff differ between flood events at the same site. Examples of classification schemes, accounting for various causative flood mechanisms at the same site is the analysis of Hirschboeck (1988), who analysed flood processes in Arizona based on surface and upper weather maps, and the classification of flood peaks of the Coquihalla river in Canada into two process types by Waylen and Woo (1982). Merz and Blöschl (2003) proposed a process typology of floods in Austria. They used a combination of a number of process indicators including the timing of floods, storm duration, rainfall depths, snowmelt, catchment

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state, runoff response dynamics and the spatial coherence of floods, all derived from observed data, to identify five different flood types in Austria, including long-rain floods, short-rain floods, flash floods, rain-on-snow floods and snowmelt floods. These flood process classifications focus, among others, on understanding the processes that can lead to flood runoff at a given site. In contrast, studies such as IH (1999), Castellarin *et al.* (2001) and Merz and Blöschl (2005) aim at predicting flood characteristics at ungauged locations using different types of information or flood indicators or catchment attributes.

Methods used in this type of study are, among others, pooling schemes and regression analyses. In flood regionalisation methods based on the pooling of catchments to homogeneous regions, catchment characteristics used as similarity measures point to important controls. Kohnova and Szolgay (2002), for example, tested different combinations of physiographic catchment characteristics for Slovak catchments. No unique combination of catchment characteristics to derive acceptable homogeneity of the pooling groups was found, but all acceptable sets of similarity measures contained a measure of the extremity of daily rainfall, an index value of the infiltration capacity of the upper soil layer and a measure of catchment size. Castellarin *et al.* (2001) tested different similarity measures for catchments in northern-central Italy. The results demonstrated that seasonality indexes and similarity measure containing both rainfall statistics and permeability information are effective for estimating flood flows. Regression equations also point to what have been found to be important controls. For example, the predictive equation for estimating the median annual flood in the UK has as its main controls catchment area, mean annual rainfall, an indicator to represent the retention of floods by reservoirs and lakes and soil indices (IH, 1999). Pfaundler (2001) developed a stepwise multiple regression model for 231 Swiss catchments, in which catchment area, mean annual maximum daily rainfall, river network density and mean permeability are used as predictive attributes for mean annual flood. Uhlenbrook *et al.* (2002) found a good correlation of flood quantiles of 29 catchments in southern Germany with catchment precipitation, catchment area, a slope parameter, the proportion of forests and the proportion of farmland. However, as the number of catchment attributes increases, it becomes more difficult to identify the role of each of the process controls because of possible interactions between the catchment attributes. The aim of this paper is to explore the controls of individual flood indicators on the shape of the flood frequency curve by analysing annual maximum flood peak data of 459 Austrian catchments. In this study the flood frequency curve is characterised by the first three statistical moments, i.e. the mean annual flood (MAF), the coefficient of variation (CV) and the skewness (CS) of the flood record. To assess the controls of the catchment attributes statistically the correlation with the flood moments is analysed for the entirety of Austria as well as for five sub-regions individually.

After a description of the data and the methodology used in this paper, the effect of catchment area is analysed as one major control, followed by an analysis of the effect of seasonality. In the remaining paper the effect of different types of flood indicators are analysed. One type of indicator is associated with the event scale and is derived from rainfall and runoff data at the event scale. Examples of the indicators used in this study are event rainfall depths for maximum annual flood events, the event runoff coefficients, the times of concentration of rainfall–runoff events and information on antecedent rainfall. The advantage of this type of indicators is that it contains information on the dynamics at the event scale, but its drawback is that it is available only for gauged catchments, i.e. where the rainfall–runoff dynamics of events have been observed. We term these types of indicators 'dynamic catchment attributes' to reflect their information on the dynamics at the event scale and information on the variability between the events.

The other type of indicator examined relates to hydrologically relevant information that is not associated with the event scale. These indicators are catchment attributes typically used in flood regionalisation studies, such as long-term mean annual precipitation, river network density, topographic information and information on the geology, soil types and land use. The advantage of these types of indicators is that they can be straightforwardly estimated for ungauged catchments as no local runoff observations are required. However, they do not contain any information on the hydrological variability at the event scale and are thus termed 'static catchment attributes', to reflect the long-term character of information.

DATA AND METHODOLOGY

Data used

In this study the series of maximum annual flood peaks of 459 catchments, with a catchment area ranging from 5 to 10 000 km^2 are used. The length of the flood records varies between 7 and 136 years, with a median of 35 years. The number of stations plotted against the flood record length is given in Figure 1. The catchments are all located in Austria.

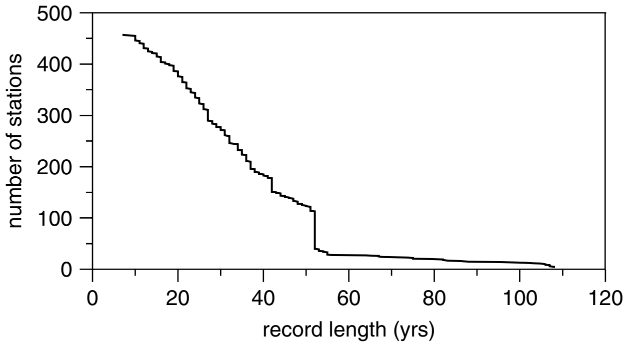

Figure 1. Number of stations plotted against the flood record length

Most of the time series are part of a database hosted by the Hydrographic Service of Austria. Additional flood peak data were obtained from hydropower companies. In a first pre-processing step the location of each gauging station was checked manually. Although the Austrian streamflow data are of excellent quality, each flood record was screened manually by visual comparison to neighbouring stations. If in doubt whether the record contains errors, the responsible staff member of the Hydrographic Services that had collected the data was interviewed. Some of the observed flood peaks were corrected as a result of the procedure or discarded from the data set (Merz *et al.*, 2007). There were only small gaps in some flood records, mainly between 1940 and 1950. Only years with observations were used to calculate flood statistics and record length. Catchment boundaries were taken from the digital river network of Austria (Fürst, 2003).

A number of hydrological relevant catchment attributes were used. To characterise runoff generation behaviour at the event scale the results of a regional analysis of rainfall-runoff events in Austria are used (Merz *et al.*, 2006), where event characteristics such as event runoff coefficients and event rainfall depth have been back calculated from hourly runoff data, hourly precipitation data and estimates of snowmelt. In total, about 120 000 events have been analysed over the period 1981 to 2000. A detailed description of the methodology is given in Merz *et al.* (2006). In addition, event rainfall, 5 day, 10 day and 20 day rainfall before the events and time of concentration (i.e. the time parameter of a linear reservoir fitted to the observed runoff hydrographs), were derived from the analysis. The data set was combined with the flood data set which resulted in a total of 5714 events that existed in both data sets.

A base flow index, i.e. the long-term ratio of base-flow to runoff, the long-term ratio of actual evaporation and rainfall (AETP) and the ratio of potential evaporation and rainfall (PETP) were calculated by simulating the catchments daily water balance dynamics using a semi-distributed conceptual catchment model (Parajka *et al.*, 2005, 2007), following the structure of the HBV model (Lindström *et al.*, 1997). The base flow index is estimated by the long-term ratio of the linear reservoir discharge representing subsurface flow and the total flow of the conceptual model. Potential evaporation (PET) was estimated by a modified Blany–Criddle method using air temperature and potential sunshine duration using the Solei-32 model (Mészároš *et al.*, 2002). Actual evaporation (AET) was estimated from potential evaporation by a piecewise linear function of the simulated soil moisture. Long-term mean annual precipitation (MAP) and information on daily precipitation were derived using over 1066 rainfall stations (Parajka *et al.*, 2007). Characteristics of hourly rainfall were derived by combining hourly rainfall data from 143 recording stations (high temporal resolution) with daily rainfall data from 1066 stations (high spatial resolution). A detailed description of the method is given in Merz *et al.* (2006). To characterise flood producing rainfall behaviour, the 95% quantiles of daily and hourly rainfall are used. The 95% quantile represent the rainfall rate that is higher than those observed on 95% of the days (hours) at each rainfall station. The station values were spatially interpolated using external drift kriging with terrain elevation as an auxiliary variable. Topographic information was calculated from a digital elevation model of Austria (Rieger, 1999). River network density was calculated from the digital river network map at the 1 : 50 000 scale (Fürst, 2003) for each catchment. Information on hydrogeology (Schubert, 2003), land use (Fürst and Hafner, 2003), and soil types (ÖGB, 2001) was also used. The lengths of the main channel in each catchment were derived from the digital river network. The lengths were calculated beginning from the catchment outlet by following the stream upwards. At a confluence, the main channel was assumed to be the stream that drains the largest catchment area. Catchment average values were then found by integration within each catchment boundary. The data sets used in the paper are summarized in Table I.

Regions

There is a large diversity of hydrological conditions in Austria, ranging from the lowlands in the east of the country, with mean catchment elevations of less than 200 m a.s.l., up to the high Alpine catchments in the west of the country with mean catchment elevations of more than 2500 m a.s.l.. Mean annual precipitation ranges from less than 400 mm year^{-1} in the east to more than 3000 mm year^{-1} in the west, where orographic effects tend to enhance precipitation. Due to the large diversity of hydrological conditions, it is likely that also the process controls on the statistical flood moments will differ across Austria. To better single out the controls on the statistical flood moments, Austria was divided into five hydro-climatic regions. The regions have been delineated manually based on an assessment of the hydro-climatic variability of Austrian catchments. The delineation of regions reflects the perception of the dominant meteorological and hydrological processes, as described below.

In Figure 2 the locations of the hydro-climatic regions are shown. Each of the analyses in this paper is carried out for the whole area of Austria, as well as for five hydro-climatic regions separately. Region 1 (termed Alpine region) covers the Alps in the west of Austria. Streamflow variability and hence flood behaviour in the catchments of this region are strongly affected by snow and glacier melt. Windward and leeward effects on north-westerly weather patterns are important. Region 2 (termed southern Alpine region) covers the Alpine catchments in East Tyrol and along the river Gail in the very south of Austria and the lower Alpine region in the south-east of Austria. The hydrological conditions are similar to those of region 1, but storm tracks from the Mediterranean are important for the flood behaviour and glacier melt is less important. In the lower part

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Table I. Data used in the project. F, S and D refer to flood data, static catchment attribute and dynamic catchment attribute, respectively (DT = data type)

DT	Information	Abbreviation	Data
F	Flood Moments	*MAF*	Mean annual flood (m^3 s^{-1} km^{-2})
		MAF_α	Mean annual flood normalised to a catchment area of $\alpha = 100$ km^2 (m^3 s^{-1} km^{-2})
		CV	Coefficient of variation of max. annual flood peaks
		CS	Skewness of max. annual flood peaks
S	Climatic indicators	*MAP*	Long-term mean annual precipitation (mm $year^{-1}$)
		AETP	Long-term ratio of actual evaporation to rainfall
		PETP	Long-term ratio of potential evaporation to rainfall
	Rainfall	*95%hourlyrain*	Hourly rainfall rate that is higher than those observed on 95% of the hours in the observation period.
		95%dailyrain	Daily rainfall rate that is higher than those observed on 95% of the days in the observation period.
	Runoff ratio	*BFI*	Long-term ratio of baseflow to runoff
S	Topography	*Elevation*	Mean catchment elevation (m a.s.l.)
		Slope	Mean topographic slope
		RND	River network density
		Channellength	Length of main channel/area (km km^{-2})
		Centrelength	Length of main channel to centre of gravity
		Channelslope	Averaged slope of main channel
S	Geology	*Quat., Limestone, Clay, Phylite, Granite*	Percentage of quaternary sediments; Percentage of limestone, dolomite and carbonate rock; Percentage of clay, marl and sandstone, Percentage of phylite and schist; Percentage of granite and gneis
	Land use	*Agricultural, Forest*	Percentage of agricultural; Percentage of forest
	Soils	*Fluvisol, Lithosol, Rendzina, Cambisol, Podsol*	Percentage of Fluvisol; Percentage of Lithosol; Percentage of Rendzina; Percentage of Cambisol and Luvisol; Precentage of Podsol
		SCSCN	SCS curve number (depending on soil type and land use)
D	Rainfall	*rain*	Event rainfall rate of maximum annual flood events
	Runoff coefficients	*rc*	Mean runoff coefficient of rainfall runoff events
		CV rc	CV of runoff coefficient of rainfall runoff events
		rc_{flood}	Mean runoff coefficient of maximum annual flood events
		$CV\ rc_{flood}$	CV of runoff coefficient of maximum annual flood events
	Time of concentration	*tc*	Mean time of concentration of rainfall runoff events
		tc_{flood}	Mean time of concentration of maximum annual flood events
	Antecedent rainfall	*5darain, 10darain, 20darain*	5 days, 10 days and 20 days antecedent rainfall prior to flood events

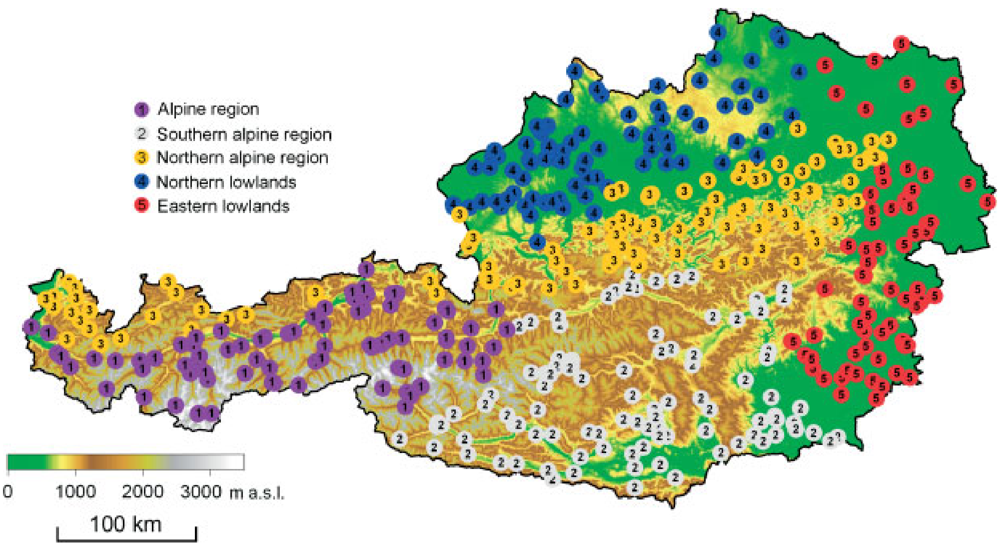

Figure 2. Location of hydrological regions in Austria. Numbers have been plotted at the location of each stream gauge

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of region 2 rainfall is significantly lower and snow processes are less important. Region 3 (termed northern Alpine region) is on the northern fringe of the central Alps. This is the region of highest rainfall in Austria, because of the orographic barrier of the Alps to north-westerly airflows. The predominant geology is limestone and dolomite. Region 4 (termed northern lowlands) in the north-west of Austria is rather flat. Rainfall is lower than in region 3, due to the smaller influence of orographic enhancement. Region 5 (termed eastern lowlands) is the driest part of Austria and is located in the east and north-east. Most of the catchments are rather flat. Much of the geology is of tertiary and quaternary origin. The eastern part of region 5 is affected by the Pannonian climate, a continental climate with warm and dry summers, and cold winters without significant snowfall. Here the lowest flood discharges in Austria are observed.

The Budyko curves of the Austrian catchments classified by region are given in Figure 3. Long-term potential and actual evaporation were calculated from daily water balance simulations using a semi-distributed conceptual catchment model (Parajka *et al.*, 2007). In terms of the Budyko curve, most of the Austrian catchments are classified as wet or humid catchments, as evaporation is mainly limited by energy. Only for some catchments in region 5, evaporation is water limited and hence these catchments are classified as dry or arid catchments. Striking are the low rates of actual evaporation in some catchments in region 1. These are the high Alpine catchments, where temperature is generally too low for higher evaporation rates. Some of these catchments are partly glaciated.

Flood Moments

To characterise the shape of the flood frequency curve the first three moments of the annual flood peak series were examined. These are the specific mean annual flood (MAF), coefficient of variation (CV) and coefficient of skewness (CS), which were estimated from the flood samples:

$$MAF = \frac{1}{m}\sum_{j=1}^{m} Q_j$$

$$S^2 = \frac{1}{m-1}\sum_{j=1}^{m}\left(Q_j - MAF\right)^2$$

$$CV = \frac{S}{MAF}$$

$$CS = \frac{m \cdot \sum_{j=1}^{m}\left(Q_j - MAF\right)^3}{(m-1)(m-2)S^3} \tag{1}$$

where Q_j is the maximum observed annual flood peak in year j divided by catchment area and m is the number of years in the flood sample.

The moments of the flood peak series for each catchment are associated with some uncertainty or estimation error due to measurement errors, different observation periods and limited record length. The uncertainty due to measurement errors is assumed to be minimised by the extensive manual check of each flood peak observation described earlier. Flood records covering different observation periods may introduce some bias in estimating the flood moments due to the presence of high flood and low flood years (Hurst, 1951). However, it is assumed that the bias due to different observation periods is much smaller, than the uncertainty introduced by the limited record length. Thus the total available records are used to estimate the flood moments. The estimation error due to the limited record length decreases with the size of the sample (number of years of the flood record) and increases

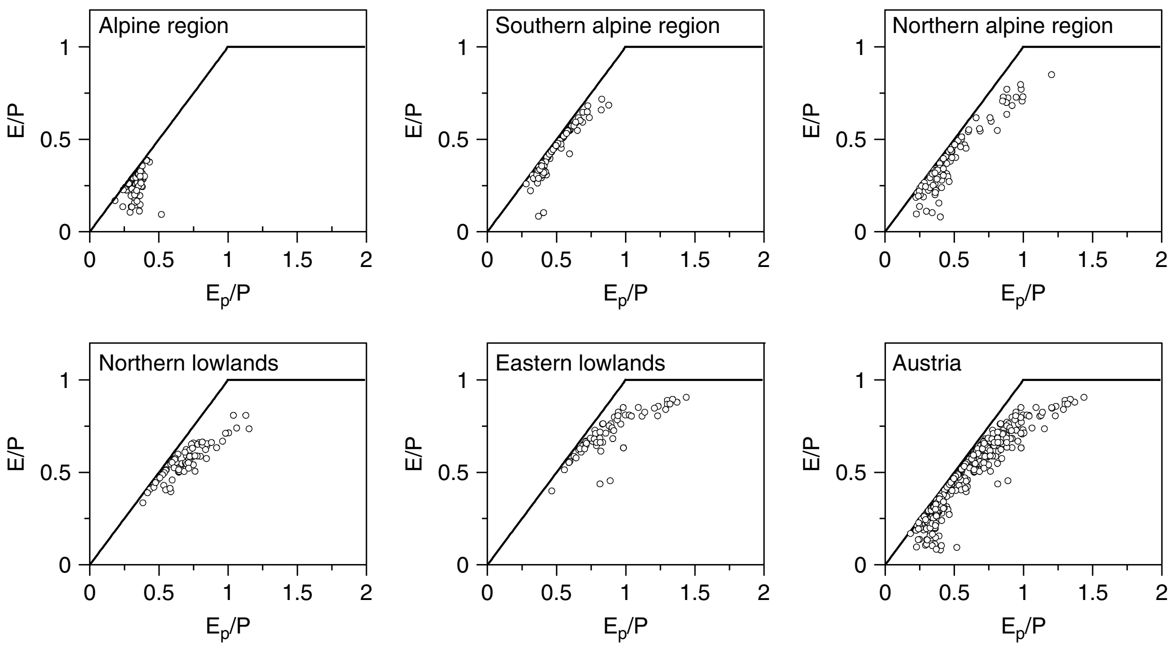

Figure 3. Budyko curves of Austrian catchments

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with the order of the moment. We estimated the estimation error due to short record lengths in a Monte Carlo analysis by drawing samples of a given size from a known distribution and estimating the coefficient of variation of the moments between different samples (Figure 4). The distribution was assumed to be the General Extreme Value (GEV) distribution with $MAF = 0{\cdot}35$, $CV = 0{\cdot}54$ and $CS = 1{\cdot}58$ (Table II). From Figure 4 it is clear that the first moment (the mean) can be estimated from a flood peak record with relatively little error while the third moment (the skewness) is always associated with substantial error, e.g. for a record length of 25 years, the uncertainty of *CS* (in terms of the coefficient of variation between different samples) is 0·69, while it is 0·11 and 0·19 for *MAF* and *CV*, respectively

A map of *MAF, CV* and *CS* of the 459 Austrian catchments used in this study is shown in Figure 5. Distinct regional patterns exist. *MAF* tends to be high in catchments at the northern rim of the high Alps (region 3). In that area, *MAF* is higher than 0·4 $m^3\ s^{-1}\ km^{-2}$, in some catchments larger than 0·8 $m^3\ s^{-1}\ km^{-2}$. In the higher alpine catchments (region 1) *MAF* tends to be somewhat smaller, with values usually between 0·2 and 0·4 $m^3\ s^{-1}\ km^{-2}$. In the lowlands of eastern Austria (region 5) the smallest *MAF* are observed, with values usually lower than 0·2 $m^3\ s^{-1}\ km^{-2}$. The patterns of *CV* show an opposite trend to the patterns of *MAF*. In the lowlands of eastern Austria (region 5), where the smallest *MAF* values are observed, *CV* tends to be high with values larger than 0·8. At the northern rim of the high Alps (region 3), where *MAF* tend to be high, *CV* is small. *CS* tends to be high in the eastern lowlands (region 5), in region 2 and in region 1, while smaller *CS* values are observed in the other regions of Austria.

The patterns of *MAF* and *CV* suggest that there is a strong link between the magnitude of the statistical flood moments and the hydro-climatic variability in Austria. In the dryer eastern part (i.e. region 5), where long-term mean annual rainfall (*MAP*) and long-term mean runoff

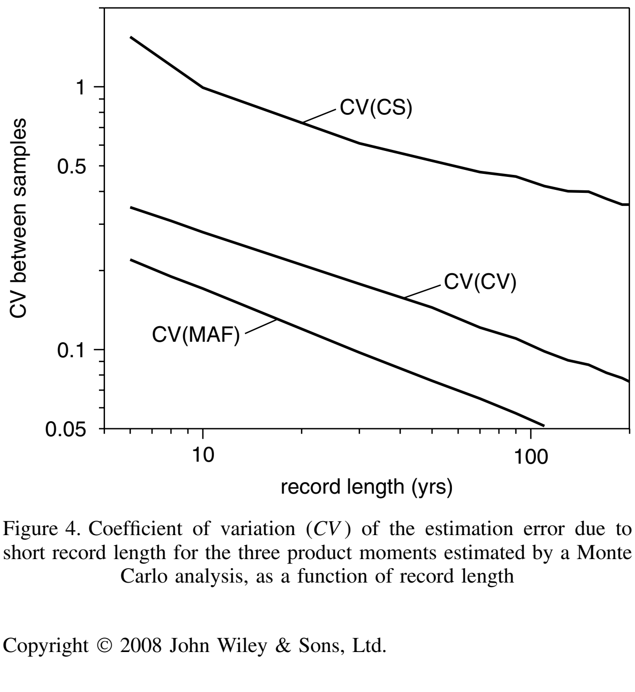

Figure 4. Coefficient of variation (*CV*) of the estimation error due to short record length for the three product moments estimated by a Monte Carlo analysis, as a function of record length

Table II. Number of stations, mean and *CV* of the first three product moments of catchments with a flood record longer than 25 years in Austrian and for each region separately. MAF_α is the mean annual flood ($m^3\ s^{-1}\ km^{-2}$) normalised to a catchment area of $\alpha = 100\ km^2$ according to Equation (3)

		No. of stations	Mean	CV
Austria	*MAF* ($m^3\ s^{-1}\ km^{-2}$)	335	0·30	0·82
	MAF_α	335	0·35	0·65
	CV	335	0·54	0·40
	CS	335	1·58	0·58
Region 1	*MAF* ($m^3\ s^{-1}\ km^{-2}$)	68	0·33	0·59
	MAF_α	68	0·36	0·39
	CV	68	0·44	0·31
	CS	68	1·86	0·49
Region 2	*MAF* ($m^3\ s^{-1}\ km^{-2}$)	77	0·19	0·60
	MAF_α	77	0·23	0·52
	CV	77	0·46	0·35
	CS	77	1·32	0·59
Region 3	*MAF* ($m^3\ s^{-1}\ km^{-2_2}$)	77	0·50	0·65
	MAF_α	77	0·52	0·52
	CV	77	0·52	0·33
	CS	77	1·50	0·55
Region 4	*MAF* ($m^3\ s^{-1}\ km^{-2}$)	40	0·28	0·62
	MAF_α	40	0·25	0·53
	CV	40	0·67	0·42
	CS	40	2·06	0·58
Region 5	*MAF* ($m^3\ s^{-1}\ km^{-2}$)	45	0·11	0·62
	MAF_α	45	0·14	0·59
	CV	45	0·72	0·32
	CS	45	1·33	0·60

is low (Parajka *et al*., 2005), *MAF* tends to be small, while *CV* tends to be high. In wetter regions, e.g. the northern rim of the high Alps (region 3) where the highest *MAP* rates are observed, *MAF* tends to be high, while most of the *CV* values are smaller. The spatial variability of *CS* cannot fully be explained by the hydro-climatic variability in Austria, but may be a result of individual extreme flood events. For example, in August 2002 an extreme Vb-cyclone (Mudelsee *et al*. 2004) caused much higher flood discharges in most catchments in northern Austria than observed before. For example, the flood peak in August 2002 of the Kamp river at Zwettl was three times higher that of the second highest observed flood peak in the period 1951 to 2001 (Gutknecht *et al*., 2002). This event resulted in a large *CS* of 5·1, while removing the single 2002 flood peak from the 51 year flood record reduces *CS* to 1·14. A significant change in *CS* due to the extreme 2002 floods is found in many catchments in northern Austria. Moreover it is clear from Figure 4 that the uncertainty of CS due to the limited observation length of flood records is much larger than for MAF and CV. Analysis of *CS* in the remainder of this paper hence needs to be interpreted with care.

Correlations

As the flood moments and the catchment attributes are not necessarily normally distributed the Spearman rank correlation coefficient (r_s) was used here to measure

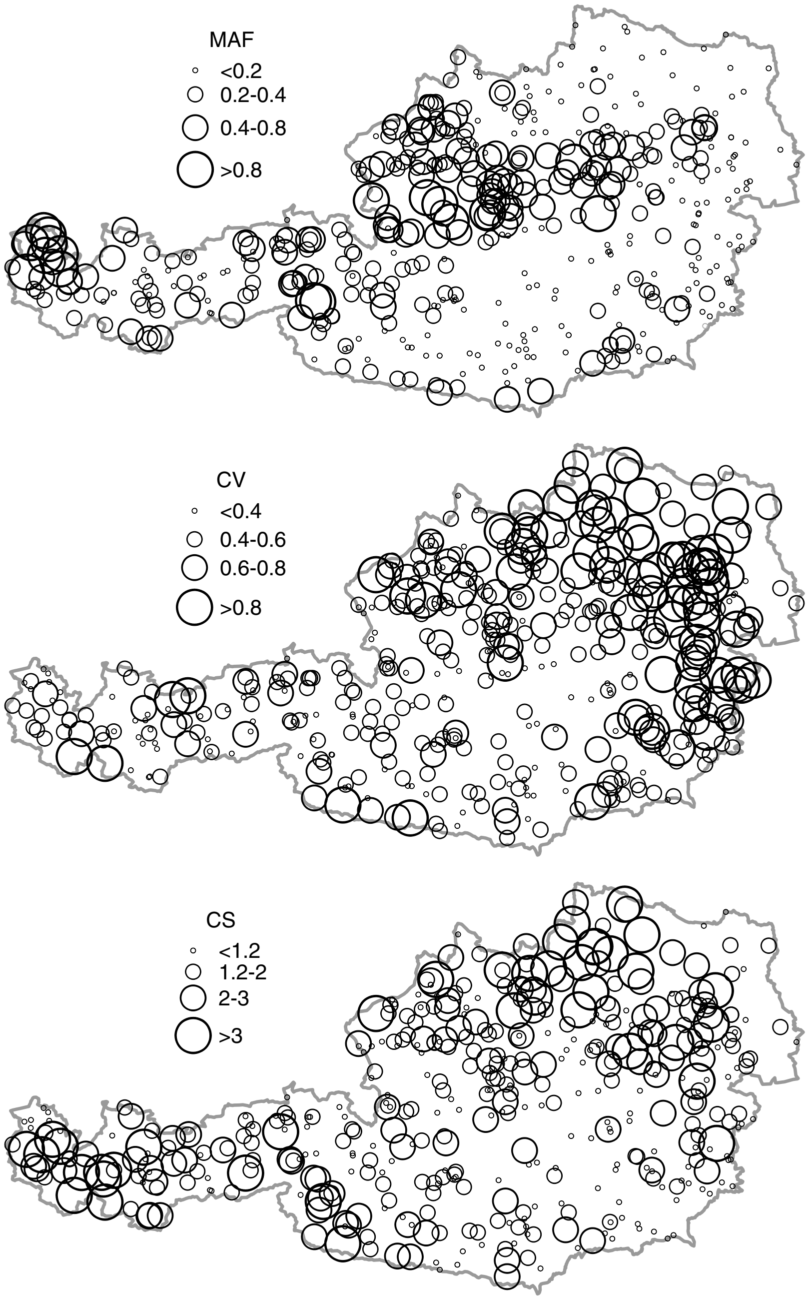

Figure 5. Mean annual floods (*MAF*) (m^3 s^{-1} km^{-2}), coefficient of variation (*CV*) and skewness (*CS*) of annual maximum flood of 459 Austrian catchments

the dependence of the flood moments on the catchment attributes:

$$r_s = 1 - \frac{6 \cdot \sum_{i=1}^{n} d_i^2}{n \cdot (n^2 - 1)} \quad \text{with} \quad d_i = rk(x_i) - rk(y_i) \tag{2}$$

where $rk(x_i)$ is the rank of x_i, where the highest value has rank 1 and the lowest value has rank n. Spearman's r varies between -1 and 1, where -1 represents a completely negative correlation and 1 represents a completely positive correlation. Completely uncorrelated pairs of data have a Spearman's r of 0. Due to the expected uncertainty in the flood moment estimation due to a short record length (Figure 4), the correlation analyses are only carried out for catchments with a flood record longer than 25 years.

RESULTS

Catchment area

In small catchments, local effects such as the occurrence of spatially limited, high intensities rainfall bursts of convective origin or local geological peculiarities may affect the shape of the flood frequency curve. In large catchments such effects may be averaged out while other processes, such as routing may become more important. It is hence likely that catchment area has a major effect on the shape of the flood frequency curve.

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In Figure 6 the statistical moments have been plotted against catchment area. All the statistical moments show a large variability. *MAF* (Figure 6a) varies between 0·01 m^3 s^{-1} km^{-2} and 1·5 m^3 s^{-1} km^{-2}, *CV* (Figure 6c) varies between 0·25 and 1·8, while *CS* (Figure 6d) varies between 0·01 and nearly 5. *MAF* decreases with catchment area (Figure 6a) as would be expected since this is the specific annual flood. Spearman's correlation coefficient for catchments with a flood record longer than 25 years is $r = -0{\cdot}50$ (Table III). To reduce the effect catchment area may have on *MAF*, the specific flood discharges have been standardised to specific discharges of a hypothetical catchment area α according to

$$MAF_\alpha = MAF_A \cdot A^\beta \cdot \alpha^{-\beta} \qquad (3)$$

where MAF_α is the specific mean annual flood discharge for a hypothetical catchment of area $\alpha = 100$ km^2 and MAF_A is the observed specific mean annual flood of a catchment of area A (km^2). The exponent β was found by a regression of *MAF* and catchment area in a semi-logarithmic plot within each region individually. This resulted in a β of 0·2, 0·19, 0·18, 0·28 and 0·3 for regions 1, 2, 3, 4 and 5, respectively. The exponent β can be interpreted in terms of the underlying processes. For the dry region 5 (eastern lowlands) where flash floods prevail, $\beta = 0{\cdot}3$ reflects the presence of high intensity storms in small catchments while in the wet region 3 of the northern fringe of the Alps where long rain (synoptic) events prevail $\beta = 0{\cdot}18$ reflects the large scale of frontal systems. In Figure 6b the specific flood discharges standardized to a hypothetical catchment area of 100 km^2 have been plotted against catchment area. Due to the standardization, MAF_α does not depend on catchment area. The Spearman's correlation coefficient of MAF_α for the entire region of Austria is $r = -0{\cdot}02$.

The correlation of *CV* and *CS* with catchment area (Figure 6c and d) is much smaller than for the (non-standardized) *MAF*. *CV* is correlated to area with $r = -0{\cdot}24$, while *CS* has a correlation coefficient of $r = -0{\cdot}17$ (Table III). As there are no small catchments with large *CV*s, the figure suggests that *CV* increase with catchment area for small catchments in the Austrian data set. This trend can be explained by the spatial locations of the gauging stations. In Figure 7 a map of *CV* of Austrian catchments are shown, stratified by catchment area. Clearly, gauging stations that measure runoff from catchments of a given scale are not uniformly distributed over Austria. Most of the few catchments with a catchment area smaller than 20 km^2 are located in region 3, the wettest region of Austria, where *CV* tends to be small (Figure 5). In region 5, where *CV* tends to be

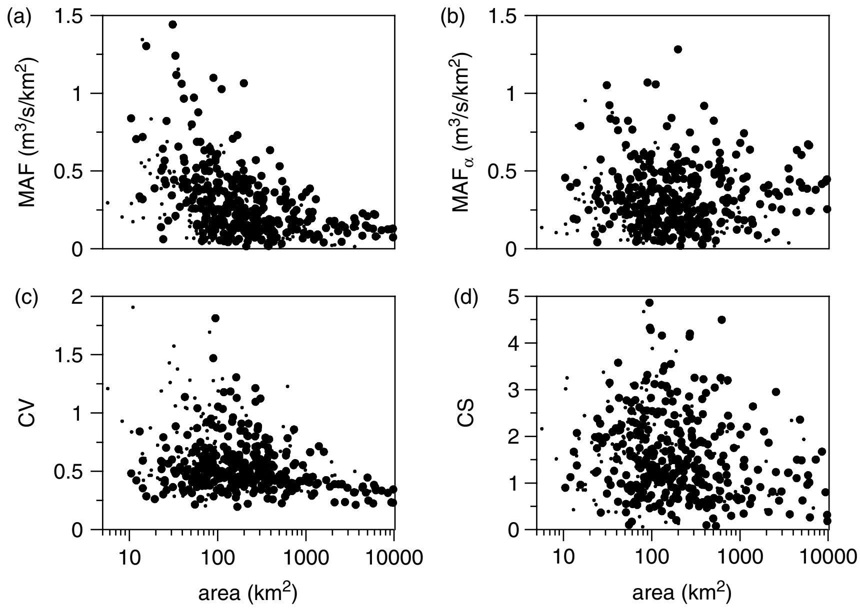

Figure 6. Statistical flood moments as a function of catchment area. MAF_α is the mean annual flood normalised to a catchment area of $\alpha = 100$ km^2. Catchments with a flood record longer than 25 years have been plotted as large dots, while small dots represent catchments with a flood record shorter than 25 years

Table III. Correlations of specific mean annual floods (*MAF*) (m^3 s^{-1} km^{-2}), coefficient of variation (*CV*) and skewness (*CS*) to catchment area of catchments with a flood record longer than 25 years. Correlation coefficients that are significant at the 95% level are printed in bold

	Austria	Region 1	Region 2	Region 3	Region 4	Region 5
MAF	**−0·50**	**−0·64**	**−0·34**	**−0·56**	**−0·48**	**−0·34**
CV	**−0·24**	**−0·33**	**−0·56**	0·08	0·09	**−0·59**
CS	**−0·17**	−0·19	**0·30**	0·08	0·13	**0·39**

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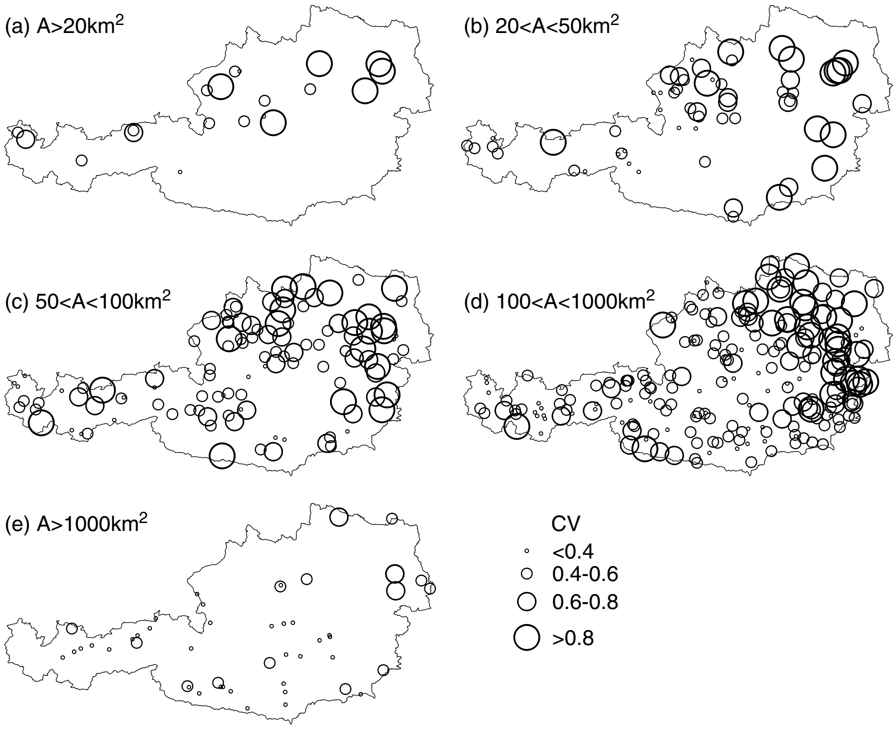

Figure 7. Coefficient of variation (CV) of maximum annual flood peaks of Austrian catchments stratified by catchment area A

high, the catchments are larger than 100 km^2. Therefore, the dependence of CV on catchment area reflects the climatic situation in which the few small catchments are located. Similarly to CV, the smaller CS values for catchments smaller than 100 km^2 is likely related to the spatial locations of the catchments.

Effect of seasonality

Recently, seasonality measures have been successfully employed as an indicator of flood processes in regional flood studies (Zrinji and Burn, 1996; Merz *et al*, 1999; Castellarin *et al*., 2001). In this study, the seasonality of maximum annual floods was quantified by using Burn's (1997) approach. Following Burn we define 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 flood series of a catchment the direction $\overline{\Theta}$ of the average vector from the origin indicates the mean date of occurrence of flood events around the year, while the length k of that vector is a measure of the variability of the date of occurrence. Values of k range from $k = 0$ (uniformly distributed around the year) to $k = 1$ (all flood events occurring on the same day). For each catchment $\overline{\Theta}$ and k are plotted on a unit circle in Figure 8, where the size of the symbols indicates different classes of MAF_α, CV and CS.

There is significant variability of seasonality between and within the regions. In region 1 (Alpine region) floods tend to occur in summer, when runoff is high because of glacier and snow melt. During winter most of the precipitation is stored in glaciers or the snow-cover. In spring to summer, depending on altitude, ice and snow melt increases antecedent soil moisture and any additional rainfall can cause flood runoff. In region 2 (southern Alpine region) the mean dates of flood occurrence vary between July and November. Floods in that region are mainly caused by two different processes. First, glacier- and snow-melt processes are important. Similar to the catchments of region 1, floods due to glacier- and snow melt processes tend to occur in summer with a strong seasonality. The second important processes are weather patterns from the south, carrying warm moist air from the Adriatic sea to Austria. Floods caused by weather patterns from the south tend to occur in October or November. Hence the seasonality of these catchments exhibits a bimodal seasonal pattern, which results in a smaller k value. A relatively weak seasonality can be found for most catchments in region 3 (northern Alpine region). Floods occur throughout all around the year with a small tendency of more summer floods. In region 3 most flood events are caused by long synoptic rainfall events (Merz and Blöschl, 2003), which can occur throughout the year. However, due to the tendency of larger rainfall events in summer and the seasonal variation in antecedent soil moisture due to snow melt, more floods occur in summer. In the lowlands of northern Austria (region 4) and eastern Austria (region 5) floods occur all around the year. This may be a consequence of a mixture of different processes contributing to runoff. In some years, floods occur during the snow melt season, when soils are saturated, while in other years, long synoptic rainfall events which occur throughout the year and short convective summer storms cause flood runoff.

The differences in the seasonal behaviour of floods in the five regions mirror, to some extent, the variability in

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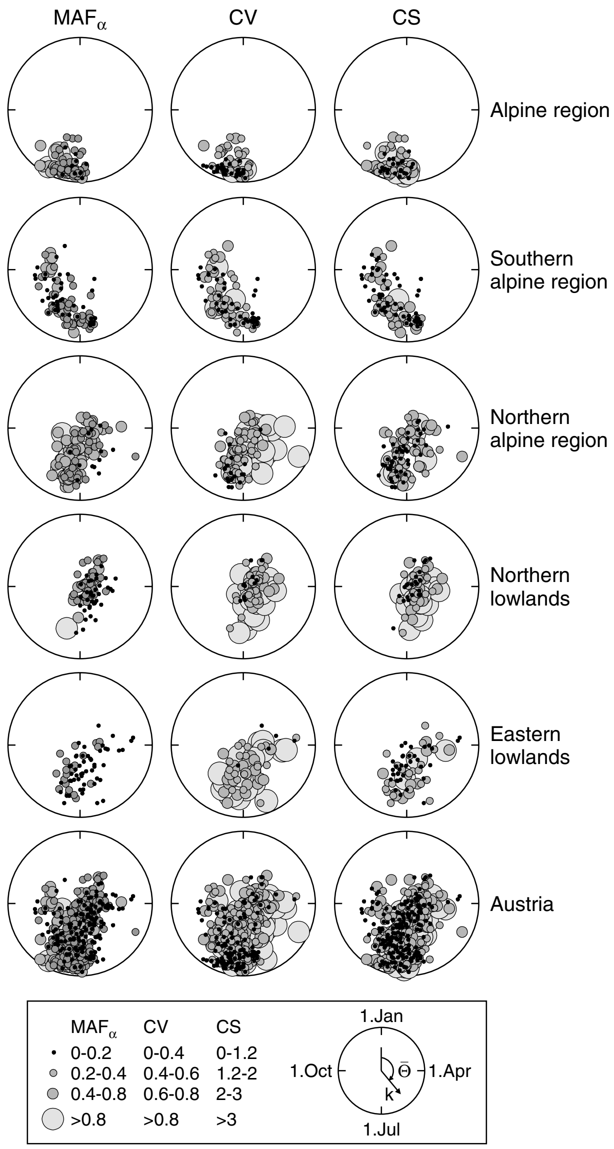

Figure 8. Seasonality of annual maximum flood peaks in Austria

the statistical moments of the flood records. In region 1, where floods tend to occur in summer with a strong seasonality, MAF_α tends to be large, while CV tends to be small. In region 4 and 5, where floods occur all around the year, MAF_α tends to be small, while CV tends to be large. This is clearly related to the underlying processes. In region 1 the flood mechanisms are similar in each year. Glacier- and snow-melt in spring increase both soil moisture and streamflow. Any additional rain can cause high flood discharges. Hence MAF_α tends to be large, while CV tends to be small. In region 4 and 5 the variability of flood producing processes is much larger. Rainfall on dry catchments is expected to result in lower flood discharges, while rainfall on wet catchments is expected to result in much higher discharges. Hence the variability in flood runoff between the years is much larger, reflected by a large CV. MAF_α, is smaller, because years with lower flood discharges occur in the flood records.

While seasonal analyses and their interpretation in terms of the underlying processes are important for a range of flood applications including regionalisation (Merz and Blöschl, 2003) and for environmental purposes, no obvious dependency of MAF_α, CV and CS on the seasonality measures ($\overline{\Theta}$ and k) can be derived from the Austrian data. In each region, the moments of the flood record of catchments with a similar $\overline{\Theta}$ and k can be quite different.

Correlation with the static catchment attributes

The correlations of a large number of static catchment attributes with the flood moments for catchments with a flood record longer than 25 years are given in Table IV. The first attribute analysed in more detail is long-term mean annual precipitation (*MAP*), which characterises the hydro-climatic situation of the catchments. It is a surrogate measure of the average antecedent soil moisture state of flood events and geomorphic catchment processes. In Figure 9 *MAP* has been plotted against the flood moments for each region. There is a large variability of the flood moments between and within the regions. In the northern alpine region (region 3), MAF_α, is on average, 0·52 m^3 s^{-1} km^{-2} (Table II). Due to the effects of orographic enhancement, *MAP* values larger than 2000 mm year^{-1} are observed in some catchments. In the much dryer eastern lowlands (region 5), where *MAP* is lower than 1000 mm year^{-1} MAF_α is on average 0·14 m^3 s^{-1} km^{-2} (Table II). This means, in the wet areas of Austria MAF_α is about 3·5 times that of the dry part of Austria. Also, within each region, MAF_α tends to increase with *MAP*, except for region 1 (Alpine region), where MAF_α and *MAP* are not correlated ($r = -0{\cdot}08$). For the other regions, r varies between 0·51 (region 2) and 0·62 (region 4). CV shows an opposite behaviour to MAF_α. In wet regions CV tends to be small, while larger CVs are observed in the dryer regions. In region 3, CV is, on average, 0·52, while in region 5 CV is, on average, 0·72 (Table II). Within the regions CV is negatively correlated to *MAP*, except region 1, where CV and *MAP* are positively correlated ($r = 0{\cdot}32$) and region 2 and 5, where no correlations exist. Other surrogate measures of the antecedent soil moisture state used in this study are the long-term ratio of actual evaporation and rainfall (*AETP*) and the ratio of potential evaporation and rainfall (*PETP*). Both indicators are negatively correlated with MAF_α and positively correlated with CV (Table IV). This is hardly surprising as both indicators are indices of climatic catchments drivers.

The analysis of the correlation of *MAP, AETP* and *PETP* suggests that one control of the statistical flood moments on Austria is the hydro-climatic situation of the catchments. Wet catchments, i.e. catchments with high *MAP* and low *AETP* and *PETP* ratios, tend to have higher flood discharges, but the variability between the years tend to be smaller. Thus MAF_α tends to be high, but CV is lower. In dry catchments, i.e. catchments with lower *MAP* and higher *AETP* and *PETP* ratios, flood discharges tend to small (low MAF_α), but larger

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Table IV. Correlation of mean annual floods normalised to a standard catchment area of $\alpha = 100$ km (MAF_α), coefficient of variation (CV) and skewness (CS) and static catchment attributes of catchments with a flood record longer than 25 years. Correlation coefficients that are significant at the 95% level are printed in bold

	Austria			Region 1			Region 2			Region 3			Region 4			Region 5		
	MAF_α	CV	CS	MAF_α	CV	CS	MAF_α	CV	CS	MAF_α	CV	CS	MAF_α	CV	CS	MAF_α	CV	CS
MAP	**0·70**	**−0·37**	−0·04	−0·08	**0·32**	−0·05	**0·51**	0·00	0·15	**0·61**	**−0·63**	−0·19	**0·62**	**−0·59**	**−0·47**	**0·57**	−0·05	−0·01
AETP	**−0·70**	**0·50**	−0·01	**−0·58**	0·13	0·04	**−0·63**	−0·16	**−0·28**	**−0·46**	**0·67**	0·10	**−0·64**	**0·64**	**0·45**	**−0·57**	**0·26**	0·15
PETP	**−0·63**	**0·39**	0·03	0·07	−0·37	0·08	**−0·61**	**−0·30**	**−0·37**	**−0·56**	**0·58**	0·11	**−0·63**	**0·59**	**0·46**	**−0·56**	0·09	0·11
95%hourrain	**0·47**	**−0·40**	−0·06	0·07	−0·02	**0·34**	**0·41**	**0·36**	0·10	**0·50**	**−0·53**	−0·06	**0·62**	**−0·65**	**−0·53**	**0·55**	**−0·32**	**−0·39**
95%dayrain	**0·43**	**−0·28**	**−0·15**	−0·01	**0·41**	−0·03	**0·35**	**0·32**	0·11	**0·47**	**−0·45**	−0·05	**0·61**	**−0·59**	**−0·46**	**0·63**	−0·13	−0·20
BFI	**−0·56**	**0·35**	0·01	**−0·42**	−0·01	**−0·32**	**−0·34**	0·04	0·03	**−0·64**	**0·58**	0·20	**−0·35**	0·19	0·14	**−0·35**	0·15	0·28
Elevation	**0·28**	**−0·47**	**0·15**	0·19	−0·23	**0·32**	**0·34**	0·01	**0·36**	**0·22**	**−0·45**	0·10	−0·19	0·14	0·20	**0·53**	0·05	0·05
Slope	**0·39**	**−0·46**	0·08	0·05	−0·12	0·00	**0·50**	0·01	**0·35**	0·05	**−0·30**	0·21	**0·47**	**−0·26**	−0·20	**0·56**	−0·04	0·00
RND	0·01	**0·19**	**−0·12**	−0·13	**0·41**	−0·17	−0·17	0·10	**−0·29**	0·22	0·05	−0·08	**0·24**	−0·17	−0·06	**0·38**	−0·06	−0·17
Ch.length	**−0·17**	**−0·20**	**−0·21**	−0·11	**−0·29**	−0·20	0·06	**−0·48**	**−0·31**	0·10	−0·02	−0·04	−0·14	0·17	0·16	0·03	**−0·39**	**−0·47**
Centrelength	−0·20	**−0·16**	**−0·18**	−0·08	**−0·27**	−0·14	−0·01	**−0·51**	**−0·32**	0·16	−0·02	−0·01	**−0·28**	**0·28**	0·18	−0·03	**−0·49**	**−0·34**
Ch.slope	**0·25**	**−0·22**	**0·18**	0·07	**0·30**	**0·25**	0·24	**0·25**	**0·37**	0·16	−0·22	0·07	−0·02	0·05	0·14	**0·41**	0·09	0·04
Quat.	**−0·17**	**0·13**	**−0·16**	−0·19	0·01	−0·24	−0·16	−0·16	**−0·29**	−0·14	−0·02	−0·26	−0·13	0·08	0·15	−0·22	−0·27	**−0·32**
Limestone	**0·50**	0·09	0·01	**−0·35**	0·17	0·04	**0·34**	0·10	−0·04	−0·14	0·06	−0·01	—	—	—	0·34	0·12	0·08
Clay	0·04	**0·33**	−0·02	0·15	**0·68**	0·28	0·26	**0·55**	−0·14	0·19	0·12	−0·01	0·23	−0·27	−0·29	−0·26	−0·07	−0·04
Phylite	−0·04	−0·08	0·14	−0·24	0·18	−0·04	**−0·35**	0·03	0·24	—	—	—	—	—	—	0·14	0·33	0·24
Granite	0·07	0·05	**0·39**	**0·47**	−0·02	**0·28**	0·13	0·09	0·14	—	—	—	**−0·45**	0·28	0·36	−0·07	0·12	0·26
Agricultural	**−0·26**	**0·25**	−0·01	−0·17	**0·39**	−0·18	−0·09	0·09	0·00	0·05	0·00	−0·07	0·08	−0·24	**−0·26**	**−0·32**	−0·15	−0·24
Forest	−0·02	0·08	**−0·16**	**−0·24**	0·12	**−0·29**	−0·22	−0·05	**−0·24**	−0·05	0·12	0·01	−0·10	0·27	0·25	**0·36**	0·16	0·18
Fluvisol	0·08	−0·14	**−0·25**	—	—	—	0·28	**−0·45**	−0·33	—	—	—	—	—	—	−0·43	0·18	0·20
Lithosol	0·05	−0·03	0·03	0·18	0·02	−0·22	0·04	0·26	**0·33**	0·01	−0·25	−0·18	—	—	—	—	—	—
Rendzina	**0·28**	**0·27**	0·08	−0·02	−0·13	0·03	**0·43**	0·31	0·10	−0·13	0·21	0·06	—	—	—	−0·14	0·21	0·04
Cambisol	**−0·29**	**0·25**	−0·10	−0·23	0·18	0·01	**−0·51**	−0·05	**−0·26**	0·07	0·10	−0·05	**0·36**	**−0·34**	**−0·40**	0·25	−0·02	0·18
Podsol	−0·22	0·10	0·24	−0·21	0·38	0·48	−0·44	−0·08	0·08	—	—	—	—	—	—	—	—	—
SCSCN	−0·06	0·06	0·03	**0·45**	−0·04	0·21	−0·08	0·20	0·02	0·01	0·02	0·04	**0·36**	**−0·42**	**−0·45**	**0·47**	−0·12	−0·19

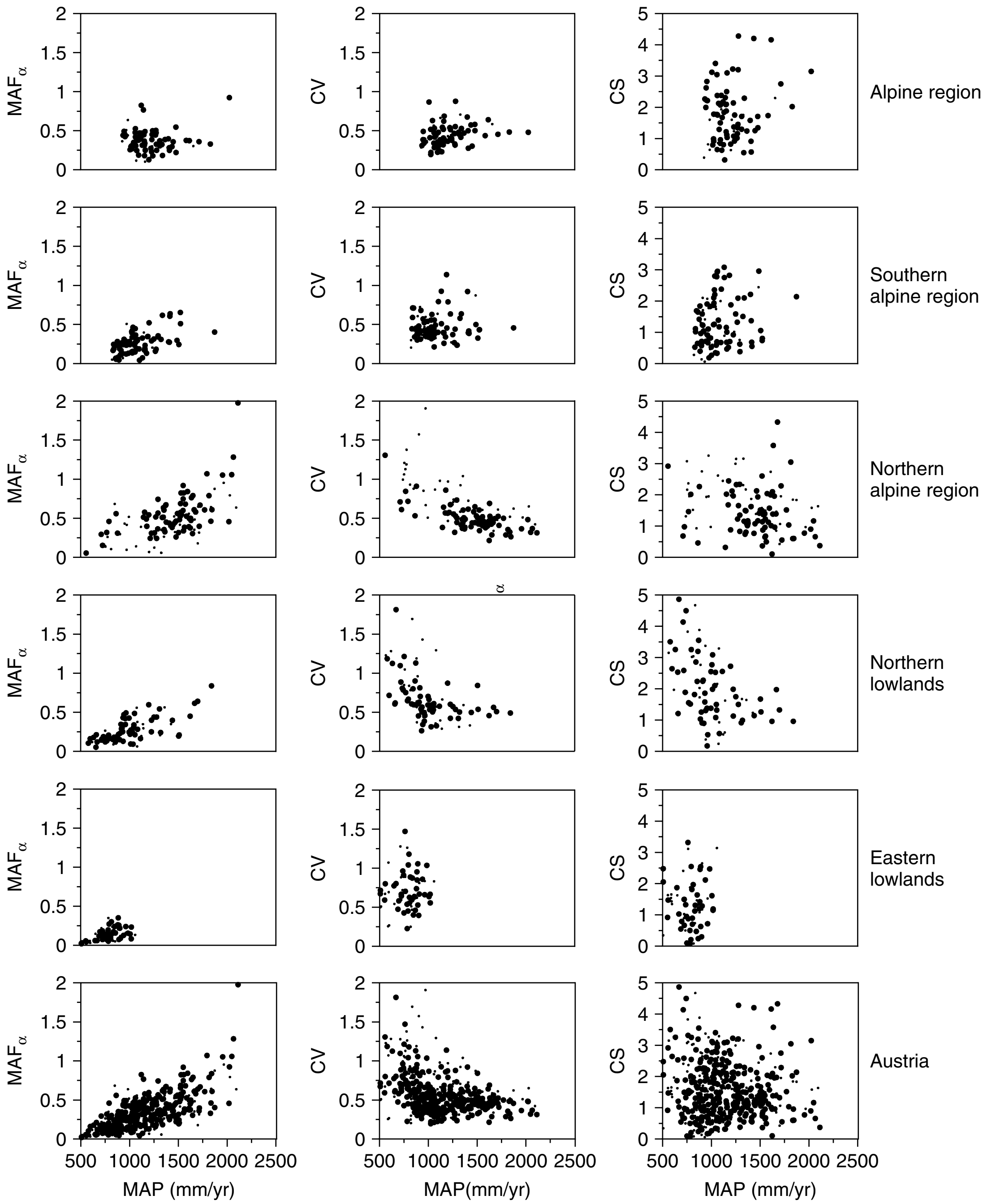

Figure 9. Statistical flood moments plotted against long-term mean annual precipitation (*MAP*). Catchments with a flood record longer than 25 years have been plotted as large dots, while small dots represent catchments with a flood record shorter than 25 years

flood discharges can occur occasionally, which results in a higher *CV*. This climatic trend is found for the entire Austrian data set, as well as for each region separately, except for region 1, where the low correlation of *MAP* and *PETP* with MAF_α results from glaciered catchments. Excluding the catchments of region 1 where more than 40% of the area is covered by glaciers or rocks, the correlation coefficient of MAF_α and *MAP* increases from −0·08 to 0·19. The correlation coefficient of MAF_α and *PETP* decreases from 0·07 to −0·32. In glaciered catchments floods tend to occur during the melt period (Figure 8), where soil moisture is high independent of *MAP*.

To characterise possible rainfall forcing of flood runoff, the 95% quantiles of hourly and daily rainfall are examined. It is assumed that these indicators contain information on how much precipitation input is to be expected on average for a single flood event. As expected, both rainfall indicators are positively correlated to MAF_α and negatively correlated to *CV* (Table IV). If more rainfall is expected for flood events on average, mean flood runoff will be higher, but the variability between the events will be smaller. For consistently high rainfall rates during flood events large parts of the catchment always contribute to runoff, while for lower rainfall rates, some parts will contribute, while other parts will not contribute.

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This increases the variability between the events and hence increases *CV*.

The base flow index (*BFI*) is a static catchment attribute and represents the ratio of subsurface flow to the total flow. As flood runoff is assumed to be dominated by surface flow and/or near subsurface flow, one expects that the more water infiltrates to form subsurface flow (and hence increases the base flow index), the smaller flood runoffs are. This is corroborated by the Austrian data (Figure 10) by a negative correlation of MAF_α and base flow index with $r = -0{\cdot}56$ for the entire Austrian data (Table IV), and a negative r for each region separately. *CV* is positively correlated with the base flow index, with $r = 0{\cdot}35$ for the complete Austrian data set. Clearly a high portion of base flow leads to a more uniform distribution of flood peaks across the year and hence to smaller *CV* s.

Other static indicators that may contain information on runoff generation during flood events are topographic indices, river network density, the SCS curve number and the percentage area covered by a geological unit, soil type or land use class. The correlation of all these indicators to the flood moments is rather weak or non-existent. The highest correlation coefficient for MAF_α

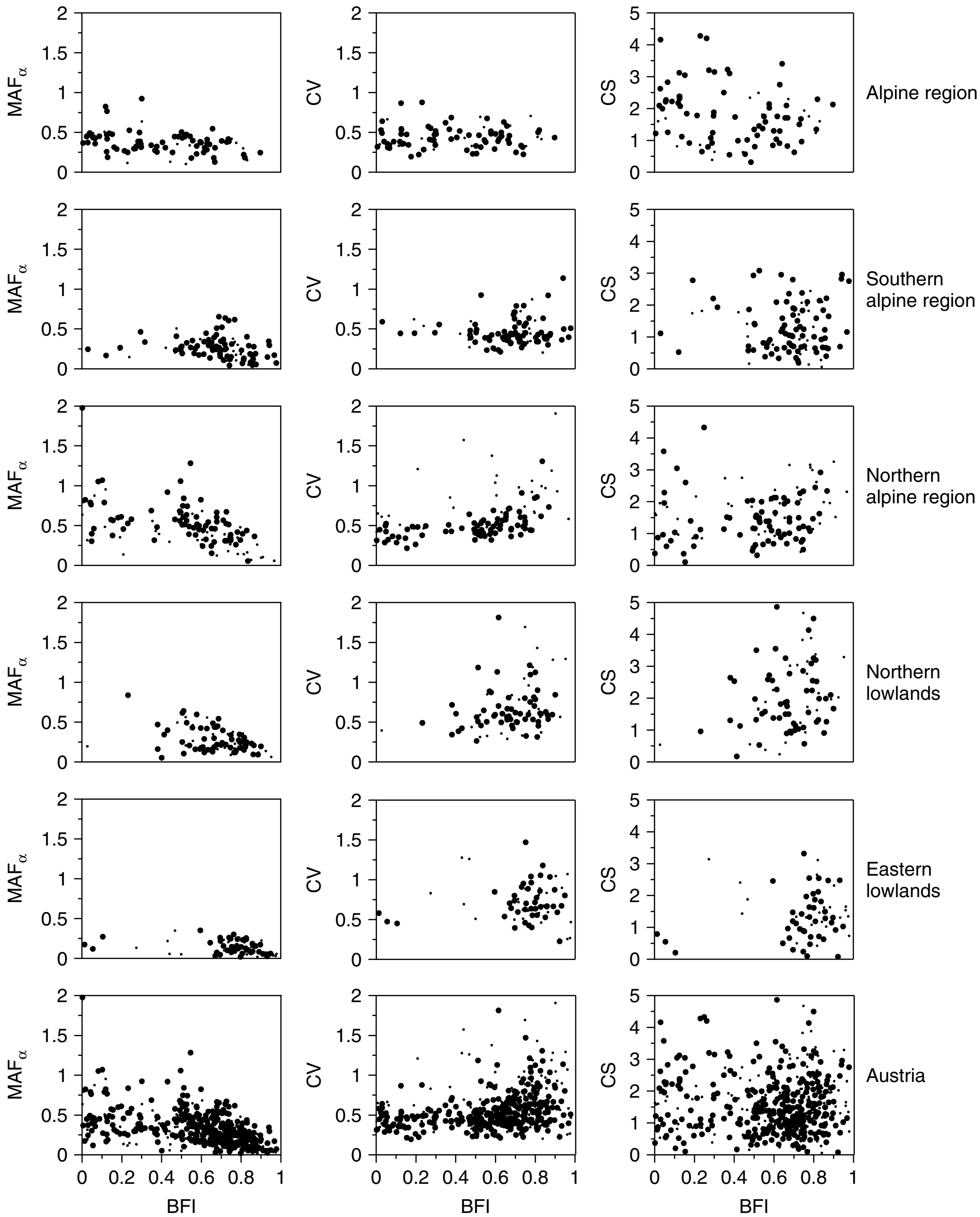

Figure 10. Statistical flood moments plotted against the base flow index (*BFI*). Catchments with a flood record longer than 25 years have been plotted as large dots, while small dots represent catchments with a flood record shorter than 25 years

is found for the percent of limestone, dolomite and carbonate for the entire Austrian data set, with $r = 0{\cdot}5$. However, this is likely to be a spurious correlation. Limestone, dolomite and carbonate are the predominant geological unit in region 3 (northern Alpine region), the region with the highest MAF_{α} values. However, the high MAF_{α} values in that region are more likely due to the wet hydro-climatic situation which is mirrored in the large MAP values (Figure 9). Within region 3, a relatively weak negative correlation between MAF_{α} and the percentage of limestone has been found. The high correlation between the percentage of clay, marl and sandstone and CV in region 1 and 2 results from a few catchments, while for most of the catchments in these regions, the percentage of clay, marl and sandstone is zero. The higher correlation coefficients between CV and elevation and between CV and topographic slope in Austria and in region 5 are likely to be a spurious correlation too. The driest catchments with the highest CV values are located in the flat lowlands of eastern Austria, while in the wetter Alpine parts in western Austria, CV values tend to be lower. This holds also for region 5. In the wetter western part of region 5, with steeper catchments of higher altitude, the climate is much wetter than in the flat catchments in the very dry lowlands in the eastern part. Hence the correlation of CV and topographic indices reflects the dependency of CV on climate.

The low correlation of the static catchment attributes with the flood moments suggests that geology, land use, soil types etc. have only a minor control on the flood discharge, which seems to be in conflict with hydrological literature, e.g. the rich literature on land-use change effects on flood runoff (Jones, 2000; Bronstert *et al.*, 2002; Robinson *et al*, 2003; Andreassian 2004; Blöschl *et al.*, 2007) and it is also in conflict with hydrological practice, where, for example, soil type related catchment attributes are used in multiple regression to predict flood runoff in ungauged catchments (IH, 1999, Merz and Blöschl, 2005).

There may be two reasons for the conflicting results. First, in this study a large area covering a wide range of hydro-climatic conditions are analysed, while most other studies on the effects of geology and land use on flood runoff have focused on one or a few catchments with a much lower hydro-climatic variability. In comparing dry and wet catchments at the regional scale, the soil moisture state seems to be a more important control on flood runoff, while geology, soil type and land use, seem to be more important in a region, where the catchment soil moisture is much more similar. This is indicated, by the tendency of higher correlations of the static catchment attributes in individual regions where they are dominant, compared with the correlations for the entire Austrian data set. The second reason for the conflicting results may be the information used in this study. The percentage area of a given geological unit, soil type or land use apparently does not contain much hydrologically relevant information and this is illustrated by the following example. In Figure 11 the geological

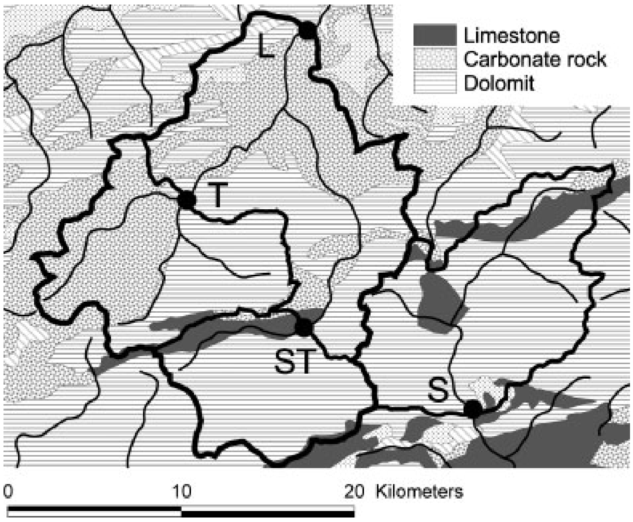

Figure 11. Hydrogeology of the Unrechtstraisen at St. Aegyd (ST) (54 km^2 catchment area) and neighbouring catchments (Traisen at Türnitz (T) (103 km^2 catchment area), Traisen at Lilienfeld (L) (333 km^2 catchment area), Schwarza at Schwarzau (S) (128 km^2 catchment area))

formation of four catchments in lower Austria are shown. The four catchments are quite similar in terms of the static catchment attributes, characterised by mean values or percentage of catchment area as shown in Table V. However, the data indicate that the flood discharges at St. Aegyd are only about 20% of those of the neighbouring catchments (Figure 12, top; St. Aegyd is labelled as 'ST'), so the runoff processes probably differ. The hydrograph for St. Aegyd (thick solid line in Figure 12 bottom) is indeed completely different from those of the other catchments (thin dashed lines in Figure 12 bottom) although the rainfall (Figure 12 centre) in all catchments was similar. The three neighbouring catchments (Türnitz (T), Lilienfeld (L), Schwarzau (S)) exhibit an early small runoff peak at hour 45 and a strong increase in runoff between hours 70 and 90, both in response to rainfall. In contrast, St. Aegyd shows no response at hour 40 and a small peak at hour 85. The early phase of the event is important and is shown in the inset graph. It appears that the base flow at St. Aegyd is much larger than that of the other catchments. The combined evidence of the delayed response to rainfall and large base flows suggests that substantial subsurface flows must occur during the event. Indeed, field surveys in the St. Aegyd catchment indicate that local gravel deposits in the valley exist that are sufficiently thick to control the local runoff regime. The geology of St. Aegyd is similar to that of the Schwarzau catchment and consists of larger areas of dolomite than the Türnitz and Lilienfeld catchments (Table V). It is the location of the gravel deposits in the limestone near the stream that produces the retarding effect rather than the total area. This suggests that the controls of geology cannot be represented well by the percentage of catchment area of a given geological unit. However, indicators of the effectiveness of geology, land use and soil types to generate runoff for a given rainfall input are usually only available for individual catchments based on

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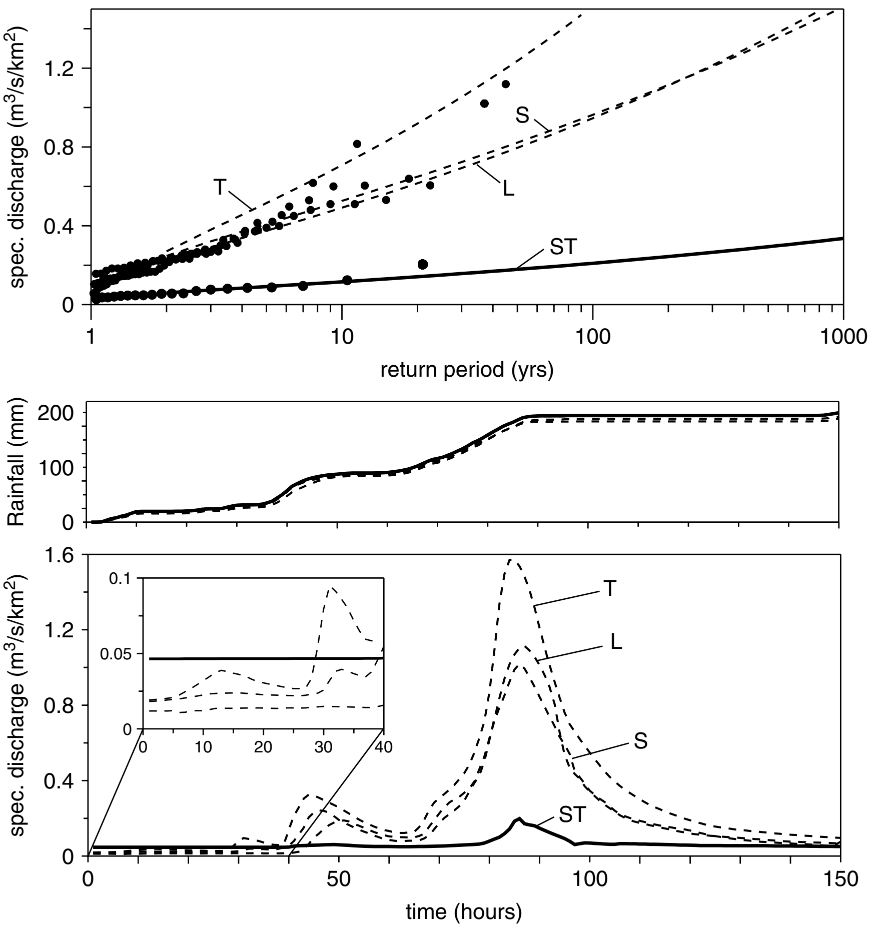

Figure 12. Top: Flood frequency plots of the Unrechtstraisen at St. Aegyd (ST) (54 km^2 catchment area) and neighbouring catchments (Traisen at Türnitz (T) (103 km^2 catchment area), Traisen at Lilienfeld (L) (333 km^2 catchment area), Schwarza at Schwarzau (S) (128 km^2 catchment area)). Bottom: Hyetographs and hydrographs of the flood event 4–10 July 1997

intensive field studies (Zehe and Blöschl, 2004; Rezzougg *et al.*, 2005) but are not available at the regional scale.

A surrogate measure of the effects of land use, soil type and antecedent soil moisture on runoff is the widely used SCS curve number classification (US SCS, 1972). Large curve numbers are associated with large runoff coefficients, while low curve numbers are associated with lower runoff coefficients. Interestingly, no correlations between the SCS curve number and the flood moments are obtained for the entire Austrian data set (Table IV). The tables of the SCS curve number method that are used to estimate the CN from land use and soil type do not seem to apply to the catchments of the study area even though they are widely used in many countries. This discrepancy is related due the spatial patterns of forest and agricultural land in Austria. In the SCS method forest is associated with small curve numbers, because of the large infiltration into forest soils. Forest is the dominant land use class at the northern rim of the high Alps (region 3), but this is a region of persistent rainfall events caused by orographic enhancement, which produces large MAF_{α}. The Austrian data hence suggests that climate is a much stronger control on the flood moments than land use or soil types for the scale analysed in this paper. In a region with a less climate variability, e.g. region 5 with MAP ranging between 500 and 1000 mm year^{-1}, the correlation of the SCS curve number and MAF_{α} is much higher ($r = 0{\cdot}47$). Static catchment attributes that are assumed to be indicators of the routing of flood runoff within the catchments are main channel length, channel length to the centre of gravity and averaged slope of main channel. The correlations are similar to those of other static indicators representing runoff generation (Table IV).

No significant correlation can be found between *CS* and any static catchment attributes used in this study except for region 4. This may be a result of single outliers, dominating the patterns of *CS* as described earlier, and sample uncertainty. Most catchments with long flood records are located in region 4 and most flood records in that region are free of outliers as no extreme regional flood events were observed in the last 100 years. Hence stronger correlation of *CS* and catchment attributes representing climate in region 4 is found. *MAP* and the 95% quantiles of hourly and daily rainfall are negatively correlated with *CS*, while *AETP* and *PETP* are positively correlated with *CS*. Similar to *CV, CS* tends to be high in dry catchments while in wet catchments *CS* tends to be lower.

Correlation with the dynamic catchment attributes

In Figure 13 the mean of the runoff coefficients of flood events with the largest peaks for each year (rc_{flood}) have been plotted against the statistical moments of each catchments. The correlation coefficients of the flood moments and rc_{flood} are given in Table VI. There is a clear trend of increasing MAF_α with increasing rc_{flood}, and a decrease of CV with increasing rc_{flood}. For the entire Austrian data set, the correlation coefficient between MAF_α and rc_{flood} is 0·78, while $r = -0{\cdot}3$ for CV and rc_{flood}. The trend of increasing MAF_α and decreasing CV is also apparent within each region and between the regions, e.g. in region 4 $r = 0{\cdot}67$ for MAF_α and $r = -0{\cdot}56$ for CV. This means, that in catchments with higher runoff coefficients, flood runoff tends to be large, but there is a lower variability of the flood runoff between the years. In contrast, in catchments with lower runoff coefficients, flood runoff tends to be lower, but larger floods can also occur so CV is larger. A significant negative correlation is found for CS and rc_{flood} in regions 3, 4 and 5. In dry catchments, where runoff coefficients are usually small, extreme floods can occur occasionally, which results in high CS values. In wet catchments, with, on average, larger runoff coefficients, the CS tends to be smaller. A negative correlation is found for MAF_α and the coefficient of variation of the

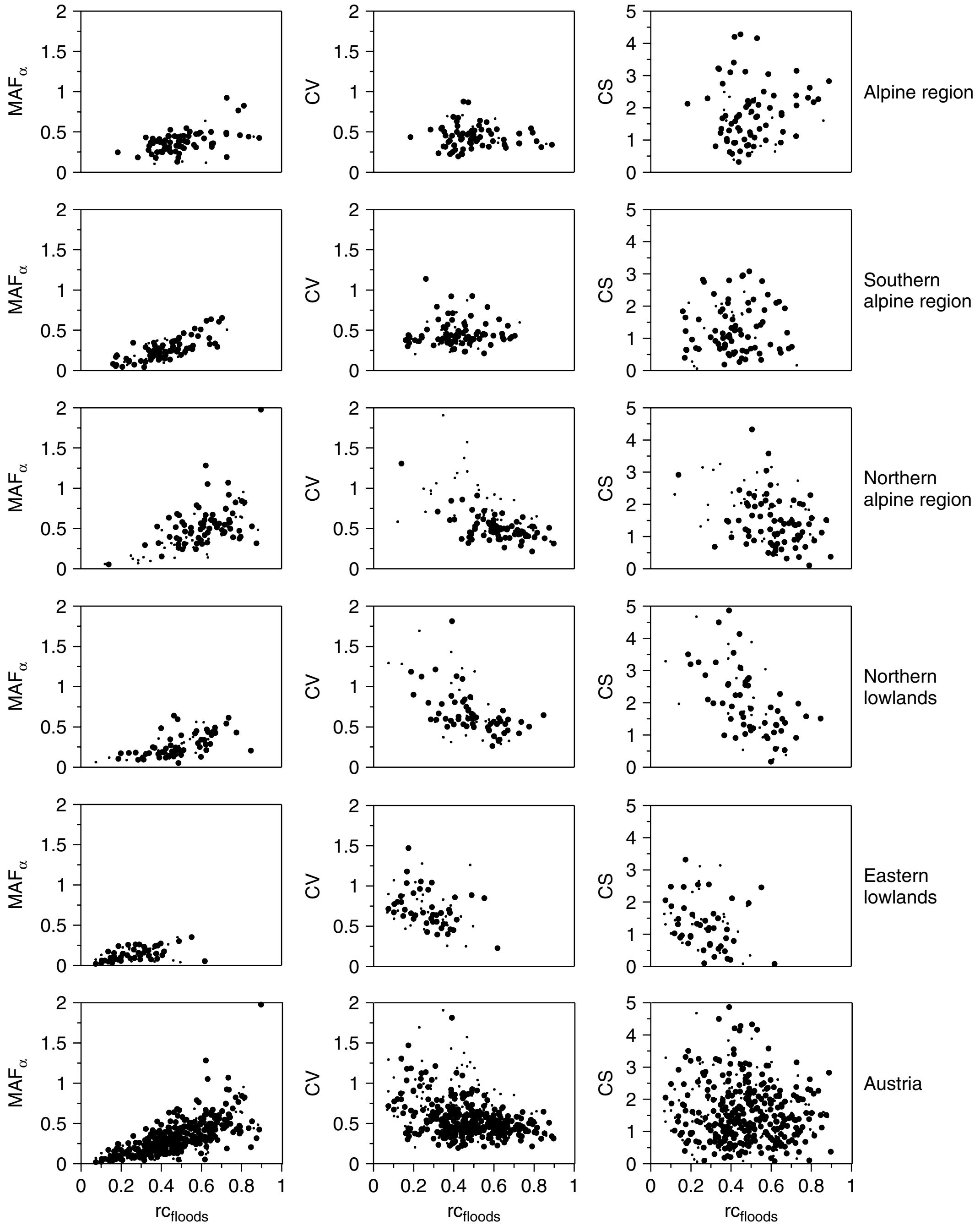

Figure 13. Statistical flood moments plotted against mean event runoff coefficient of maximum annual flood peaks (rc_{floods}). Catchments with a flood record longer than 25 years have been plotted as large dots, while small dots represent catchments with a flood record shorter than 25 years

Table V. Catchment attributes of St. Aegyd and neighbouring catchments

	Unrechtstraisen at St. Aegyd	Traisen at Türnitz	Traisen at Lilienfeld	Schwarza at Schwarzau
Label in Figure 11 and 12	ST	T	L	S
Catchment area (km^2)	54	103	333	128
Mean topographic elevation (m)	859	810	759	827
Mean topographic slope (%)	32	34	33	26
Maximum channel length (km)	9	12	30	19
Limestone (%)	15	3	5	15
Dolomite (%)	83	47	54	81
Carbonate rock (%)	2	50	39	2
Rendzina (%)	100	100	95	100
Fluisol (%)	0	0	5	0
Forest (%)	87	89	89	92
Grass (%)	12	9	10	7
Mean annual precipitation (mm)	1325	1329	1289	1225

flood runoff coefficients ($CVrc_{floods}$). In catchments, where the runoff coefficients of the maximum annual flood events do not vary much between the years, MAF_α tend to be high and *CV* tends to be low. In catchments with a larger variability of the runoff coefficients, the *CV* of flood runoff is, of course, larger and MAF_α tends to be smaller.

Merz *et al.* (2006) found that the main controls of event runoff coefficients in Austria are climate and runoff regime through the seasonal catchment water balance and hence antecedent soil moisture, in addition to event characteristics. In wet catchments, runoff coefficients of flood events tend to be large with a lower variability between the events, which results in larger MAF_α and lower *CV*. In dryer catchments, runoff coefficients tend to be small and hence MAF_α tends to be smaller. However, large runoff coefficients can occur, if rarely, which can lead to much larger runoff peaks and hence the *CV*s of the flood records tend to be larger than in wet catchments.

To illustrate the effect of runoff coefficients on the flood frequency curve, two examples are shown in Figure 14. The left graphs relate to the Bregenzer Ache catchment at Au which is located in the west of Austria at the northern rim of the Alps (region 3). Due to orographic enhancement of north-westerly airflows, rainfall is high and persistent with mean annual precipitation of more than 1800 mm $year^{-1}$. The runoff coefficients in the figure are taken from Merz *et al.* (2006) and have been plotted against the return period of the peaks of the associated flood events. The runoff coefficients range between 0·4 and 0·8 for small events, while for two events larger than the 10 year flood (one of them is the largest observed flood), the runoff coefficients are about 0·6. All other flood events of a return period larger

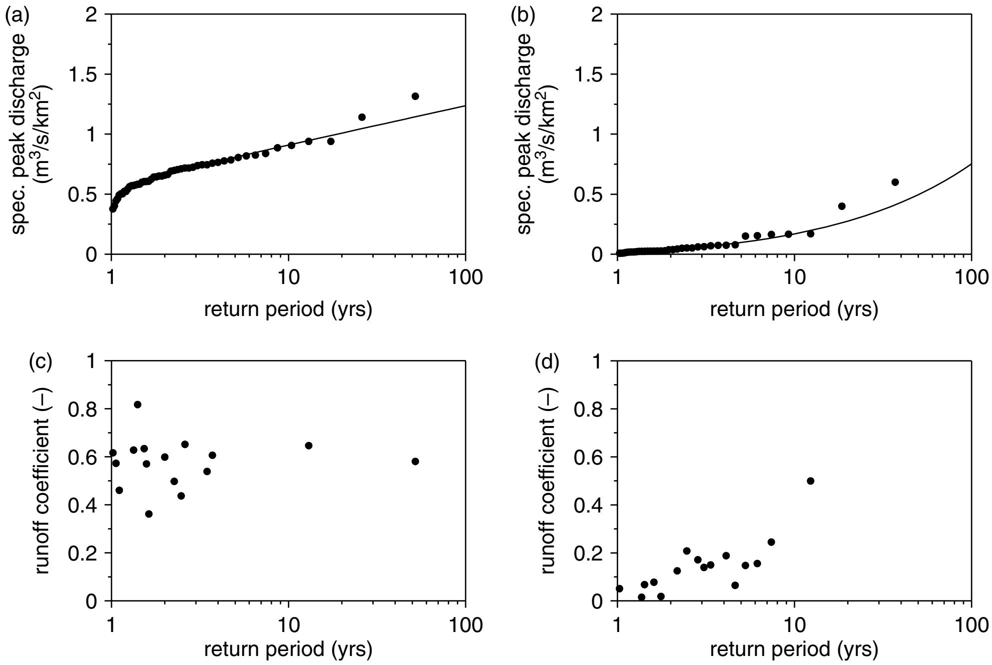

Figure 14. Flood frequency plots (top) and runoff coefficients of the associated flood events (bottom) Left: Bregenzer Ache at Au (149 km^2 catchment area). Right: Tauchenbach at Altschlaining (90 km^2 catchment area)

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Table VI. Correlation of mean annual floods normalised to a standard catchment area of $\alpha = 100$ km (MAF_α), coefficient of variation (CV) and skewness (CS) and dynamic catchment attributes of catchments with a flood record longer than 25 years. Correlation coefficients that are significant at the 95% level are printed in bold

	Austria			Region 1			Region 2			Region 3			Region 4			Region 5		
	MAF_α	CV	CS	MAF_α	CV	CS	MAF_α	CV	CS	MAF_α	CV	CS	MAF_α	CV	CS	MAF_α	CV	CS
rain	**0·39**	**−0·47**	0·01	0·02	−0·05	**0·17**	0·13	−0·33	0·00	0·28	−0·49	0·00	0·07	−0·39	−0·12	**0·24**	−0·17	−0·03
rc_{flood}	**0·78**	**−0·30**	−0·06	**0·64**	−0·02	0·14	**0·74**	−0·13	0·06	**0·56**	**−0·47**	**−0·33**	**0·67**	**−0·56**	**−0·60**	**0·53**	**−0·41**	**−0·35**
$CVrc_{flood}$	**−0·22**	**0·16**	0·09	−0·05	0·03	**−0·30**	−0·06	−0·12	0·18	−0·15	0·22	0·10	−0·19	**0·36**	0·24	**−0·51**	0·16	**0·32**
rc	**0·76**	**−0·51**	**−0·04**	**0·62**	**−0·29**	**0·09**	**0·65**	**−0·14**	**−0·03**	**0·45**	**−0·60**	**−0·12**	**0·75**	**−0·70**	**−0·48**	**0·51**	**−0·42**	**−0·30**
CVrc	**−0·71**	**0·49**	−0·02	**−0·48**	0·13	0·20	**−0·62**	**0·25**	0·04	**−0·32**	**0·56**	0·02	**−0·53**	**0·52**	**0·28**	**−0·50**	**0·39**	0·27
tc^*_{flood}	**−0·47**	**0·41**	**0·11**	**−0·60**	**0·40**	**0·32**	**−0·51**	**0·27**	0·14	**−0·74**	**0·43**	0·10	**−0·72**	**0·34**	0·22	**−0·49**	0·18	−0·02
tc^*	**−0·58**	**0·23**	**0·11**	**−0·62**	0·11	0·18	**−0·71**	0·08	0·06	**−0·78**	**0·38**	**0·22**	**−0·76**	**0·42**	**0·32**	**−0·31**	0·10	−0·07
5darain	**0·49**	**−0·40**	**0·14**	**0·52**	−0·14	0·28	**0·41**	−0·18	0·19	**0·27**	**−0·27**	0·20	0·09	−0·19	−0·19	**0·35**	0·02	−0·09
10darain	**0·47**	**−0·51**	0·08	**0·49**	−0·23	0·22	**0·45**	−0·20	0·15	**0·31**	**−0·46**	0·11	0·10	**−0·28**	−0·21	**0·67**	0·04	−0·05
20darain	**0·47**	**−0·54**	0·06	**0·51**	−0·15	0·29	**0·34**	**−0·28**	0·11	**0·37**	**−0·53**	0·05	**0·42**	**−0·33**	**−0·27**	**0·59**	−0·19	−0·27

than 10 years occurred before 1981, where no runoff coefficients have been analysed, but it can be assumed for these events the runoff coefficients were similar. This means that one would not expect a major increase in runoff coefficients with increasing return periods. This is reflected in the flood frequency curve which in fact shows a downward curvature on a semi-logarithmic plot and based on the analysis of the runoff coefficients one would expect that the trend continues, if the rainfall regime remains similar. The second example, the Tauchenbach at Altschlaining, is located in the flat east of Austria close to the Hungarian border (region 5). The catchment is much dryer than the first example with mean annual precipitation of about 760 mm year^{-1}. At Tauchenbach, the runoff coefficients are much lower. For the smallest floods, the runoff coefficients vary between 0·01 and 0·1 and they significantly increase with increasing return periods. The highest observed runoff coefficient is about 0·5. As rainfall becomes more extreme, one would expect that the trend of increasing runoff coefficients with increasing return period continues. For flood events of high return periods, not only event rainfall is higher but also runoff coefficients are significantly higher than for small floods. These two effects result in an upward curvature of the flood frequency curve on a semi-logarithmic plot (Figure 14d).

In addition to the runoff coefficients of the annual floods (rc_{flood}), Table VI gives the correlation between the flood moments and the mean runoff coefficients of all events (*rc*) and the coefficient of variation of all events (*CVrc*). The correlation coefficients between *rc* and MAF_α are very similar to those of rc_{flood}. This means that the tendency of wet catchments of having larger event runoff coefficients is not only observed for maximum annual flood event, but also for all rainfall–runoff events. It is interesting that the correlation between *CVrc* and *CV* is even larger than the correlation between $CVrc_{floods}$ and *CV*. This means that the non-linearity in the runoff generation is better represented by *CVrc* than by $CVrc_{flood}$. This may be a result of the uncertainty in estimating runoff coefficients of annual maximum flood events, as flood hygrographs are often subject to considerable errors as the measurement error of discharge tends to increase with discharge due to a number of reasons.

The time of concentration (tc_{flood}) of catchments during flood events, i.e. the averaged time parameter of a linear reservoir fitted to the observed flood event, is usually dependent on the catchment scale (Melone *et al.*, 2002). To avoid colinearities, tc_{flood} was standardised by catchment area

$$tc^*_{flood} = \gamma \cdot tc_{flood} \cdot A^\delta \qquad (4)$$

where tc^*_{flood} is the standardised time of concentration (hrs) and A is the catchment area (km^2). The power δ in Equation (4) has been chosen according to typical catchment scale dependences of *tc* (Melone *et al.*, 2002), while the factor γ has been chosen as $\gamma = 0·2$ to make the median value of tc^*_{flood} in Austria equal to unity (Merz and Blöschl, 2003).

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tc^*_{flood} is negatively correlated with MAF_α and positively correlated with CV. The effect of the time of concentration on MAF_α is what one would expect. As the catchment response slows (large tc^*_{flood}) the mean flood peaks decrease. This relationship is significant at the 95% level. As the catchment response slows, the data indicate that CV increases, which may be a result of the lower MAF and a similar variance. In a similar way the time of concentration of all events (tc) is negatively correlated with MAF_α and positively correlated with CV.

The average antecendent rainfall of a given duration (5 days, 10 days and 20 days) is positively correlated with MAF_α and negatively correlated with CV as would be expected. With increasing rainfall, soil moisture and hence the runoff coefficients increase, which results in higher flood peaks. If average antecedent rainfall is, on average, lower, individual large rainfall may still occur, which increases the variability of the runoff coefficients and hence the CV of flood runoff. It is interesting that the correlation of antecedent rainfall of a given duration with the flood moments tends to be higher than for the event rainfall. For example $r = 0{\cdot}49$ is the correlation between MAF_α and 5 day antecedent rainfall, and $r = 0{\cdot}39$ for MAF_α and event rainfall for the entire Austrian data. This indicates that flood runoff is, on average, more strongly controlled by the catchment moisture state than by the rainfall input during the event. In Austria, most maximum annual flood events are caused by long duration synoptic or frontal type storms (Merz and Blöschl, 2003). Rainfall over several days, or possibly weeks, including low-intensity rainfall, can saturate the catchment and can cause high flow conditions. Once the storage capacity of the catchment is reached any additional rainfall will generate a flood event. Note that the higher correlation of antecedent rainfall compared with event rainfall may be related to low or medium flood events. As the magnitude of the event increases, antecedent soil moisture becomes relatively less important and event rainfall becomes more important. This is supported by extreme event analyses (Gutknecht *et al*., 2002).

The dynamic catchment attributes used in this study are hardly correlated with CS, except in region 4, where flood records tend to be longer. Similarly to the case of the static catchment attributes, this may be related to sample uncertainty and the presence of outliers in the flood sample.

DISCUSSION AND CONCLUSIONS

There are seven main observations from the analyses in this paper.

(1) A strong dependency on catchment area of the mean annual specific floods of Austrian records was found. For all Austrian catchments used in the study, as well as for each region separately, mean annual specific floods tend to decrease with increasing catchment area. This dependency is, of course, consistent with many flood data sets analysed in the literature and is taken advantage of in specific discharge–area diagrams, which are widely used in operational hydrology to estimate flood discharges in ungauged catchments. Normalising the specific discharge of each catchment to a hypothetical catchment area of $\alpha = 100\ \text{km}^2$ helped to better appreciate the other controls on the mean annual flood. The variability of the CV of Austrian catchments gives a pattern that is very similar to that found by Smith (1992) for 104 catchments in the central Appalachian region. He suggested that there may exist a consistent relationship between CV and catchment scale, but Robinson and Sivapalan (1997), based on a derived flood frequency model, suggested CV may increase for small catchments and decrease with catchment area for larger catchments. This was attributed to the interaction between time scales of storm duration and catchment scale for small catchments, while for larger catchments the decrease in CV was suggested to be due to the spatial scaling of rainfall. In this paper, the increase in CV with area for small catchments is attributed to the location of the catchments. There are essentially no small catchments in the regions with large CVs, which results in an apparent scale dependency. Region 5 is climatologically dry and CVs tend to be large, but no small catchments are gauged, while most small catchments are located in region 3, which is climatologically wet and CVs tend to be small. This indicates that catchment area is not a major control on CV. This is consistent with the results of Blöschl and Sivapalan (1997), who analysed the dependence of CV on catchment area for 489 Austrian catchments, which is a similar data set to that used in this study. Based on a derived flood frequency model, they found a complex interplay of a number of processes and concluded that area is not the most important control on regional CV.

(2) Differences in the seasonality of floods in the five regions can be found. The variability in the seasonal behaviour can be interpreted in terms of the underlying processes, which, to some extent, are related to the magnitudes of MAF_α and CV. For example, there is a difference in the seasonal behaviour of region 1 and 5 (summer versus all year floods), and the flood moments differ too. In region 1 (Alpine region) floods tend to occur in summer, when runoff is high because of glacier and snow melt, while in region 5 (Eastern lowlands) a mixture of different processes contribute to runoff and hence floods occur all around the year. The differences in CV are related to the different underlying processes. Merz and Blöschl (2003) found, that the CV of flood samples stratified by process types is lower for snowmelt floods and rain-on-snow floods, while CV is larger for rainfall driven floods. Hence CV tends to be lower in region 1 and higher in region 5.
However, no direct dependence of the flood moments on the seasonality measures is apparent in the data. This indicates that seasonality analysis may be used

in identifying regional dominant processes for the delineation of homogeneous regions, but care must be taken in using seasonality directly in flood regionalisation on a catchment to catchment basis. Similar seasonality between two catchments does not necessarily imply that the statistical flood moments are similar.

(3) The analysis of the Austrian data suggests that, for this type of climate and scale of catchments, the main controls on the statistical flood moments are climate and the runoff regime through the seasonal catchment water balance and hence antecedent soil moisture. Surrogate measures of climate such as long-term mean annual precipitation, long-term potential and actual evaporation are significantly correlated with *MAF* and *CV*. A similarly strong correlation is found for the mean event runoff coefficient of flood events, which is a consequence of the effect of the seasonal water balance on runoff coefficients in Austria (Merz *et al*., 2006). In a wet climate, catchments tend to be wet prior to most flood events and hence the runoff coefficients are, on average, high. The high runoff coefficients result in higher flood discharges with a relatively low variability in discharges between the events. Hence, in wet catchments, *MAF* tends to be high and *CV* tends to be small. In dry catchments, soil moisture may be low prior to most flood events and hence runoff coefficients are lower on average, which results in smaller flood discharges. For some events, the catchment soil moisture will be higher, which increases runoff coefficients and hence flood discharges. Thus, in dry catchments, flood discharges tend to be low, but higher flood discharges can occur, if rarely, which results in a much higher *CV*.

(4) No strong correlation was found for catchment attributes analysed in this study and *CS* of the flood record, except for region 4. This results from the rather erratic patterns of *CS* (Figure 5) due to single extreme flood events and sample uncertainty (Figure 4). Detailed analyses of many flood record in Austria (Merz *et al*. 2008) revealed, that indeed, observed *CS* can vary vastly in catchments, which exhibit a similar flood behaviour. The large variability likely results from the interaction of temporal varying observation periods and climate fluctuations, single extreme events and observation errors. In region 4 the flood records tend to be longer which reduces the sample uncertainty. Hence here the correlations are stronger. Similar to *CV, CS* in region 4 tends to be higher in dry catchments and lower in wet catchments.

(5) While climate and antecedent soil moisture seemed to be very important in controlling the shape of the flood frequency curve, static catchment attributes that are assumed to represent runoff generation, such as geology, land use and soil type, do not seem to exert a major control. This result needs to be interpreted in the context of the data set used. Due to the large climatic variability within Austria, climate seems to be a much stronger control than geology, soil types and land use. In wet catchments, mean flood runoff tends to be high, independent of the geological units, while in dry catchments mean flood runoff tends to be much lower.
An additional reason for the low correlation may be the use of the percentage of catchment area covered by a given geological unit, soil and land-use type to characterise the process controls on the flood frequency curve. Although this is the type of information typically used in many practical studies, it seems not to be representative for three reasons. First, the spatial arrangement of areas within the catchment can be extremely important as shown for the case of geology in a catchment in lower Austria. Cerdan *et al.* (2004) presented a similar example for the importance of the spatial arrangement of land use. Second, even within the same geological unit, soil or land-use type, the runoff generation can differ vastly, depending on infiltration capacity, preferential flow through macro pores, cracks or rills etc. as illustrated by many case studies around the world (Wösten *et al*. 2001). Third, the low correlation may also be related to scale. Most of the catchments analysed in this study are medium sized to large catchments. Once one moves to smaller scales, geology, soils and land use clearly become more important as illustrated by numerous plot scale studies (Kirnbauer *et al*., 2005). In fact, an interesting interplay appears to exist between climate, long-term landform evaluation and flood runoff (Kirkby, 2005). For example, Blöschl and Merz (2008) present three examples of landform–hydrology feedback from Austria, such as the incision of channel and runoff production and routing. However, these effects are not represented by the catchment attributes used in this study.

(6) The relative importance of different indicators to predict flood moments in Austrian catchments, is corroborated by several studies in neighbouring countries. Pfaundler (2001) for Switzerland, Konohova and Szolgay (2002) for Slovakia and Uhlenbrook *et al.* (2002) for southern Germany found that catchment area has an major control on the mean annual flood, which was expected. Also similar to Austria, these studies showed that information on precipitation seems to have more predictive power than physiographic catchment attributes. However, different rainfall indicators are applied. Pfaundler (2001) and Konohova and Szolgay (2002) used information on extreme daily precipitation, Uhlenbrook *et al.* (2002) used 24 h winter precipitation and Castellarin *et al.* (2001) used L-CV and L-CS of daily precipitation to characterise precipitation. For Slovakia (Konohova and Szolgay, 2002) and northern Italy (Castellarin *et al*., 2001) a permeability index was found to be a good predictive indicator of floods. There are no permeability indexes available in Austria at the regional scale, but event runoff coefficients represent how much water infiltrates into deeper soils and hence can

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be assumed to contain similar information as a permeability index. Thus the Slovak and Italian studies corroborate the predictive power of runoff coefficients found in Austria. Uhlenbrook *et al*. (2002) found good correlation between the proportion of forests and farmland, while in Austria these indicators seem to have no predictive power. However, Uhlenbrook *et al*. (2002) found a positive correlation for forest and a negative correlation for farmland, which seems to be against 'general hydrological knowledge'. They concluded that this results from the inter-correlation of land-use data with slope. Forests are mainly at steep sites and farmland vice versa. Although, all the studies seem to result in some common indices containing information on the statistical flood moments, there are of course regional differences in the ranking of the indicators. Beside the existing variability of hydrologic processes between regions, the differences have to be interpreted with respect to the indicators of floods available for each study. Each study uses its own set of catchment attributes and for each study catchment attributes may be derived by different methods and hence reflect different quality of information and uncertainty.

(7) The analysis of the Austrian data suggests that there is a large variability in the performance of different indicators to predict flood behaviour. Due to the strong influence of climate on flood runoff in Austria, surrogate measures of climate and seasonal water balance, such as mean annual precipitation, long-term evaporation and the base flow index consistently contain more information on the statistical flood moments than do indicators of catchment formation, such as percentage of area of a geological unit and soil types. While in other regions of the world with a lower variability in climate, geology, soils and land use may be more important this does not seem to be the case here. Much better indicators of runoff generation at the catchment scale are event runoff coefficients. However, event runoff coefficients have been derived from event runoff data and are hence not available in ungauged catchments. This underlines the importance of developing new indicators at the regional scale that are more representative of the causative flood processes than current indicators are.

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