Journal of Hydrology (2006) **331**, 591–604

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Spatio-temporal variability of event runoff coefficients

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Received 29 September 2005; received in revised form 15 May 2006; accepted 2 June 2006

KEYWORDS
Runoff coefficient;
Runoff generation;
Flood types;
Spatio-temporal variability

Summary Runoff coefficients are widely used as a diagnostic variable of runoff generation in process studies and as an important input parameter in hydrologic design. In the present study runoff coefficients have been back calculated from hourly runoff data, hourly precipitation data and estimates of snowmelt. A total of about 50,000 events in 337 Austrian catchments with catchment areas ranging from 80 to 10,000 km^2 have been analysed over the period 1981–2000. The results indicate that the spatial distribution of runoff coefficients is highly correlated with mean annual precipitation but little correlated with soil type and land use. The temporal distribution of runoff coefficients can be accurately represented by a Beta distribution. The parameters of this distribution exhibit spatial patterns that match six climatic regions of Austria. In each of the regions, event runoff coefficients increase with event rainfall depth and with antecedent rainfall but the differences between the regions are larger than those between events of different sizes. An analysis of the runoff coefficients by flood types indicates that for flash floods, runoff coefficients are smallest, and they increase, in that order, for short rain floods, long rain floods, rain-on-snow floods and snowmelt floods. It appears that in this type of climate and at the scale of the catchments examined here the main controls on event runoff coefficients are the climate and the runoff regime through the seasonal catchment water balance and hence antecedent soil moisture in addition to event characteristics. Catchment characteristics such as soils and land use affect runoff coefficients to a lesser degree.

Introduction

The event runoff coefficient is defined as the portion of rainfall that becomes direct runoff during an event. The

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doi:10.1016/j.jhydrol.2006.06.008

concept of event runoff coefficients dates back to the beginning of the 20th century (e.g. Sherman, 1932) but it is still widely used for design in the engineering practice. It is also used as a diagnostic variable to represent runoff generation in catchments, particularly if a range of catchments and a range of events are to be compared by a single indicator. Event runoff coefficients can also be used in event-based derived flood frequency models (e.g. Sivapalan et al., 2005) that estimate flood frequencies from rainfall frequencies and are useful for understanding the flood frequency controls in a particular hydrologic or climatic regime.

Although the event runoff coefficient is a key concept in hydrology, most regional scale studies, so far, have analysed a relatively limited number of events. Typically, a dozen of events in a few catchments in a region are examined. Cerdan et al. (2004), for example, analysed 345 rainfall runoff events in three catchments of different sizes in France to study scale effects in the runoff generation process. They found a significant decrease in the runoff coefficient as area increases. For catchments of the scale of 10 km^2 the percentage of arable land appeared to be a driving factor of runoff response. Naef (1993) analysed the 5–10 largest floods in about 100 Swiss catchments and concluded that the interactions of runoff coefficients and catchment condition are very complex and runoff coefficients should hence be treated as random numbers. Dos Reis Castro et al. (1999) compared runoff coefficients at different scales, ranging from small plots to catchments of several square kilometres on a basaltic plateau in southern Brazil. Gottschalk and Weingartner (1998) examined runoff coefficients of 192 flood events in 17 Swiss catchments which they used in a derived flood frequency model. They fitted a Beta function to the distribution of runoff coefficients in each catchment and interpreted the parameters for different hydrologic regions in Switzerland. They concluded that the differences in runoff coefficients can be explained by grouping catchments according to physiographic characteristics.

There exist numerous irrigation studies that have analysed runoff coefficients for the plot scale but upscaling these estimates to the catchment scale can be very difficult (Cerdan et al., 2004). Predictive equations for the event runoff coefficient at the catchment scale such as the SCS curve number method or the Lutz (1984) method in use in Germany are empirical equations, so their range of applicability is not always clear (Blöschl, 2005).

While these and other studies have shed some light on the temporal variability in any one catchment it has been notoriously difficult to separate the spatial and temporal variability of runoff coefficients. From a limited number of events it is also difficult to isolate the regional controls, such as soils and climate, and to examine the effect of event characteristics on runoff coefficients at the regional scale. The aim of this study is to analyse the spatio-temporal variability of runoff coefficients using a data set of 50,000 events. We examine the spatial and temporal distribution functions of the runoff coefficients as well as the effect of event rainfall characteristics, climate, soil characteristics, runoff regime types and flood event types on the runoff coefficients.

Data and methodology

Motivation and general approach

There are two approaches of analysing the percent contribution of rainfall to streamflow. The first approach is the event scale analysis of runoff and rainfall records. In this approach, runoff coefficients of single events are usually analysed by a three step approach: (a) separation of single events, (b) separation of observed runoff into baseflow and direct flow and (c) estimation of event runoff coefficients as the ratio of direct flow volume and event rainfall volume. The second approach consists of soil moisture accounting schemes that trace the soil moisture conditions of catchments in a continuous way. Both the event scale and continuous approaches have their strengths and weaknesses. While separation of individual events can be somewhat subjective it is a data based approach that does not require the assumptions inherent in the soil moisture accounting schemes. We have therefore chosen in this study to focus on the event based analysis.

As in this type of analysis data availability is always limited we have adopted an analysis approach that combines various data sources. We use both daily and recording raingauges in Austria and simulate snow melt to obtain representative estimates of water input to the catchments during freezing, thawing and no-snow conditions. Event runoff coefficients are usually estimated as the ratio of event runoff volume and event rainfall volume. This is straightforward if all events are clearly separated and direct runoff between events is small. However, if the direct runoff at the end of an event is significantly larger than zero this ratio will underestimate the runoff coefficient as the trailing limb of the hydrograph is trimmed. To overcome this problem we fitted a simple event rainfall-runoff model to the direct hydrograph. In this runoff model, the runoff coefficient appears explicitly as a model parameter and can hence be estimated by optimising an objective function. This procedure is less sensitive to the choice of the start and end points of the events than the usual ratio of volumes.

Catchment rainfall and snowmelt

This study is set in Austria and the study period is 1981 to 2000. To maximise rainfall information, hourly rainfall data from 143 recording stations (high temporal resolution) were combined with daily rainfall data from 1066 stations (high spatial resolution). The locations of the recording raingauges and the daily raingauges are shown in Fig. 1. In a first step daily precipitation was disaggregated to hourly values using the approach of Grebner (1995) and Grebner and Roesch (1998). In this method, the temporal rainfall pattern within a day at a daily rain gauge is estimated as a distance-weighted sum of the temporal rainfall patterns at four relevant recording stations. Those recording stations are deemed relevant that are closest to the daily rain gauge within each quadrant of a north oriented rectangular coordinate system.

In a second step, the hourly precipitation values were spatially interpolated. Ordinary kriging and inverse distance weighting were examined. A comparison of the methods

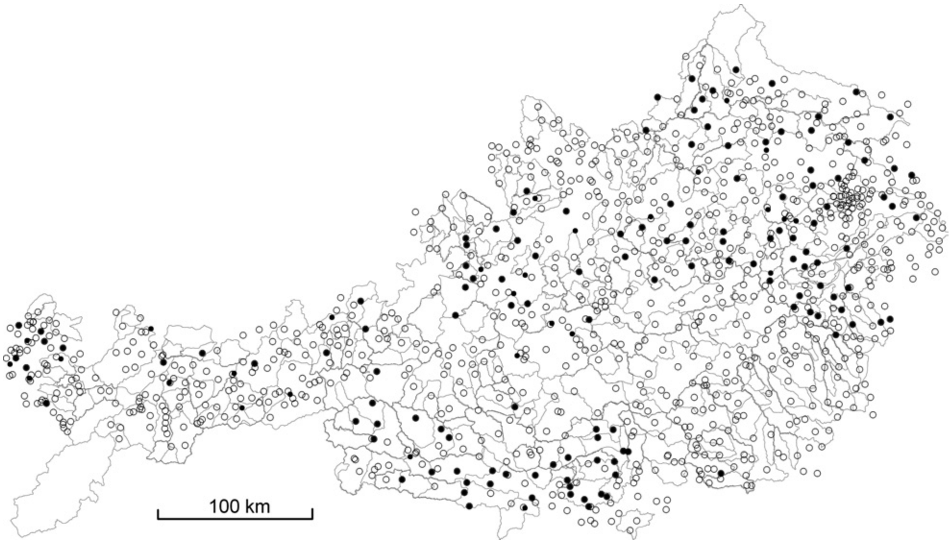

Figure 1 Recording raingauges (solid circles), daily raingauges (open circles), catchment boundaries (lines) in Austria as used in this analysis.

indicated that the differences in terms of catchment rainfall were small, so the simpler inverse distance-weighting method was used. The interpolated rainfall map for each hour was then combined with the catchment boundaries to estimate hourly catchment precipitation. To examine possible biases of the method, hourly catchment rainfall was aggregated to annual values and compared with the mean annual rainfall of Parajka et al. (2005) who used external drift kriging with elevation to regionalise rainfall. The annual values of Parajka et al. (2005), typically, were 3–5% larger, with a tendency for larger biases in higher catchments. This is mainly because most of the raingauges are in the valleys which introduces elevation biases. Rainfall measurements are also subject to catch deficit which tends to increase with elevation as snow is more frequent in higher altitudes than in the lowlands (Sevruk et al., 1998). To account for both elevation effects, catchment rainfall used in this study was increased by a factor that was allowed to vary with mean catchment elevation. The factor was set to 6% in the lowlands of Austria (elevation of 120 m a.s.l) and 35% in the highest catchments (elevation of about 3000 m a.s.l.), and assumed to increase linearly in between.

Solid precipitation during an event will not directly contribute to event runoff but snow melt from an existing snow pack will add to any liquid precipitation. To account for both effects, results from a daily water balance model (Parajka et al., 2005) for each catchment have been used. The model is a semi-distributed conceptual model and accounts for snow accumulation and snowmelt using threshold air temperatures and the degree day factor concept. The model was calibrated to daily discharges and snow cover data (Parajka et al., 2005). The daily model-simulated values were then disaggregated to hourly values. The ratio of liquid to solid precipitation was assumed constant for each day from which liquid hourly precipitation was estimated. For the temporal pattern of snowmelt during a day a truncated cosine distribution was assumed, where snowmelt started at 9 a.m., the maximum occurred at 3 p.m. and snowmelt ceased at 9 p.m.. The sum of liquid precipitation and snowmelt for each hour was used in the further analyses.

Baseflow separation

Hourly discharge data from 337 Austrian catchments with catchment areas ranging from 80 to 10,000 km^2 (median of 265 km^2) were used. Smaller catchments that were available in the region were discarded as the uncertainty introduced by the spatial rainfall interpolation was expected to be large. Larger catchments than 10,000 km^2 were discarded as the within catchment variability of runoff coefficients was assumed to be large. All discharge data were carefully screened and outliers were removed by slightly smoothing the discharge time series (Merz et al., 2004). Only catchments without significant anthropogenic impacts (Piock-Ellena and Blöschl, 1998) were used.

The event runoff coefficient relates to direct runoff or quickflow only, so it was necessary to separate quickflow and baseflow. Direct runoff arises from rainfall that contributes immediately to streamflow during an event, while baseflow contributes to streamflow with a significant delay (Fig. 2). In this study, an automatic method of baseflow separation was used. Different techniques have been proposed

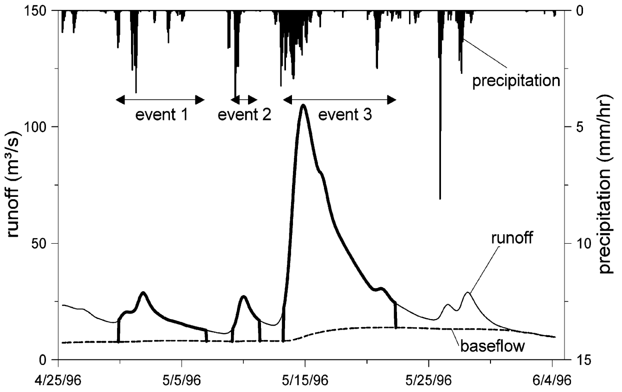

Figure 2 Separation of baseflow and runoff events. Kamp catchment at Zwettl, 622 km^2.

in the literature (Grayson et al., 1996; Tallaksen, 1995). A number of techniques were tested for the data sets of this study and the digital filter proposed by Chapman and Maxwell (1996) yielded a baseflow separation that most closely followed what one would separate manually by visual inspection. The Chapman and Maxwell (1996) filter was hence used here. It can be expressed in the form

$$q^{b}(t) = \frac{a_2}{2-a_2} q^{b}(t-\Delta t) + \frac{1-a_2}{2-a_2} q(t), \quad q^{b}(t) \leqslant q(t), \tag{1}$$

$$a_2 = e^{-\frac{\Delta t}{k_2}}, \tag{2}$$

$$q^{d}(t) = q(t) - q^{b}(t), \tag{3}$$

where $q^{b}(t)$ is baseflow, $q(t)$ is runoff t and $q^{d}(t)$ is direct runoff at time t. Δt is the sampling interval of 1 h in this study. Parameter a_2 is a function of the storage parameter k_2, which can be derived by a recession analysis. The catchments in the study area have greatly varying runoff regimes, so an automatic estimation of the recession constants is not straightforward. They were therefore estimated manually by visual inspection of the runoff data time series of each catchment and used in separating baseflow by Eq. (1).

Event separation

To separate rainfall runoff events, it is necessary to identify the start and the end of an event. This is not easy to do automatically. A procedure for event separation was developed here based on trial and error to match the event separation one would do manually. The associated parameters were also found by extensive tests and were examined for robustness.

To assist in event separation, a characteristic time scale t_c' of the runoff dynamics of each runoff peak was estimated first (Appendix). Each runoff time series was then screened starting from the largest peak flow and proceeding to the second largest peak flow and so forth according to the following method. A peak flow was assumed to be the peak flow of a potential event, if the ratio of direct runoff to baseflow $q^{d}(t_p)/q^{b}(t_p)$ at time t_p of the peak was larger than 2 and there was no larger flow in the previous and following 12 h. For each peak flow, the start of an event was searched backwards from t_p to $t_p - \eta_j \cdot t_c'$. The start of an event was assumed to be that time t_s for which

$$q^{d}(t_s) < \varepsilon_j \cdot q^{d}(t_p) \tag{4}$$

i.e. the time where the direct runoff becomes small compared to the direct runoff at the time of the peak flow. If no starting point was found, the search was repeated and η_j and ε_j were gradually increased in five iterations (j = 1—5) to η_j = 0.5; 1.0; 1.5; 2.0; 2.5 and ε_j = 0.01; 0.03; 0.1; 0.2; 0.4, respectively, to relax Eq. (4). With this iterative approach, the direct runoff at the beginning of an event is as small as possible but if no such point in time is found, a higher direct runoff is allowed. The time t_e of the end of each event was identified in an analogous way searching within t_p and $t_p + 4\eta_j \cdot t_c'$. All potential events for which the beginning and end points could be identified, for which the peak flow at time t_p was larger than any other discharge within the event, and for which $t_p - t_s$ > 3 h and $t_e - t_p$ > 6 h were considered acceptable events. In case of overlapping events only the one with the larger peak flow was retained. The approach was repeated proceeding from the largest event on record to smaller events until all events were identified, and it was repeated for all catchments.

The method was thoroughly tested by visual inspection which indicated that it can indeed identify rainfall runoff events for the runoff regimes of the study area in a similar way as manual separation. An example is shown in Fig. 2 for the Kamp catchment in Lower Austria. The method identifies small and large events which allows analysis of the runoff coefficients over a range of event sizes. In high alpine catchments where baseflow in summer is always high due to glacier and snowmelt, a separation of events is not always possible and hence the number of separated events was smaller than in the rainfall dominated catchments of the lowlands.

Estimating the runoff coefficient

The event runoff coefficients were now estimated using a simple rainfall runoff model based on a linear reservoir with storage parameter k_d and a constant runoff coefficient r_c. For each event separately, the direct runoff over the time period t_s to t_e was simulated with catchment rainfall plus snowmelt inputs over the time period $t_s - t_c'/10$ to $t_e - t_c'/10$. The two model parameter k_d and r_c were then calibrated minimizing the root mean square difference between the observed direct runoff hydrograph and the simulated direct runoff hydrograph. The shuffled complex evolution optimisation scheme of Duan et al. (1992) was used. r_c was allowed to vary between 0 and 1 and k_d was allowed to vary between $0.5t_c'$ and $40t_c'$. The calibration resulted in an event runoff coefficient for each event. An example of the calibration of an event in May 1996 in the Kamp catchment is shown in Fig. 3.

For a small number of events the rainfall runoff model could not be fitted satisfactorily to direct runoff from observed data and these were discarded. One reason for the lack of fit are measurement errors. For some events, particularly flood events, water may have bypassed the gauged cross section which may cause poor model fits. There may also by instances where the temporal dynamics of rainfall is not fully captured by the disaggregation scheme which

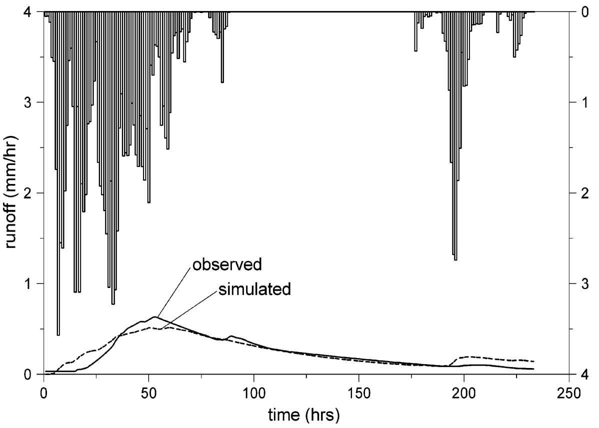

Figure 3 Example of fitting a simple runoff model to direct runoff for back-calculating the event runoff coefficient. Kamp catchment at Zwettl, 622 km^2.

may, again, give rise to poor model fits. This may particularly be the case for multiple peak events. For a total of 49,918 events the root mean square error of the fitting was less than 70% of the average direct runoff and these events were used in the analyses of this paper.

Results

Four representative catchments

To illustrate the range of event runoff coefficients, the results for four catchments that are representative of different Austrian runoff regimes are presented first. In Fig. 4 the direct runoff volumes (in terms of event runoff depth) have been plotted against the precipitation volume as the sum of rainfall and snowmelt (in terms of event precipitation depth) for all the events analysed. In Fig. 5 the cumulative distribution functions of the event runoff coefficients for these catchments are shown. The physiographic and hydrological characteristics of these catchments are shown in Table 1.

The Pitze at Ritzenried (Fig. 4a) drains a high alpine catchment. Runoff is controlled by snow processes during most of the year. The runoff coefficients are nearly uniformly distributed with a median of 0.36. The number of events is rather small (only 42), because the separation of events is difficult as snowmelt tends to increase baseflow during most of the summer. The Ois at Lunz am See catchment (Fig. 4b) is located at the northern rim of the high Alps. Due to orographic enhancement of northwesterly airflows, rainfall is both high and persistent. Fig. 3b indicates that event rainfall depths and runoff depths are the largest of the four catchments examined here. The runoff coefficients are uniformly distributed with a median of 0.55. There are a total of 159 events in the data set. The Kamp at Zwettl catchment (Fig. 4c) is located in a dryer region in the north of Austria. The direct runoff depths are much smaller than in the Lunz catchment. The distribution of

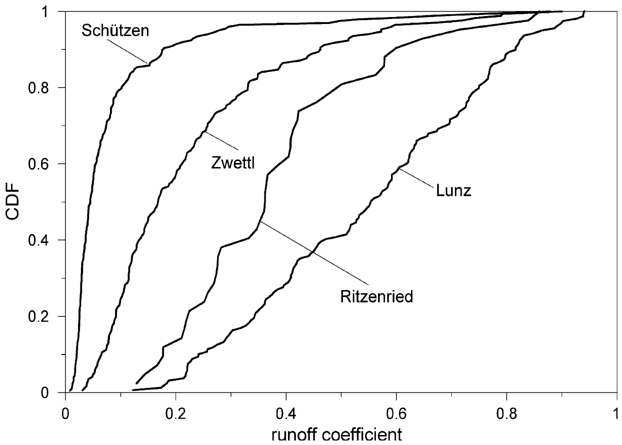

Figure 5 Distribution function of the event runoff coefficients of four catchments in Austria: Ritzenried/Pitze (220 km^2); Lunz am See/Ois (117 km^2); Zwettl/Kamp (622 km^2); Schützen am Gebirge/Wulka (384 km^2). Events with rainfall depths (including snowmelt) greater than 10 mm have been used here.

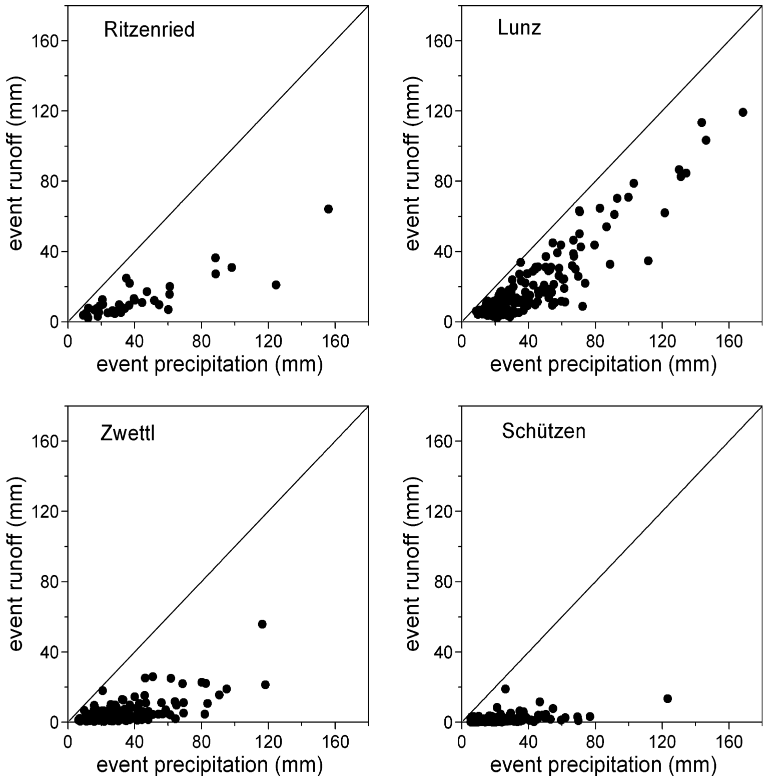

Figure 4 Event runoff depth vs. event rainfall (including snowmelt) for four catchments in Austria. (a) Ritzenried/Pitze (220 km^2); (b) Lunz am See/Ois (117 km^2); (c) Zwettl/Kamp, (622 km^2); (d) Schützen am Gebirge/Wulka (384 km^2).

Table 1 Catchment attributes of the four catchments of Figs. 4 and 5

Catchment	Ritzenried/Pitze	Lunz an See/Ois	Zwettl/Kamp	Schützen am Gebirge/Wulka
Area (km^2)	220	117	622	384
Mean elevation (m a.s.l.)	2547	1061	734	226
Mean slope	0.50	0.33	0.07	0.05
Geology	Granite, gneiss, schist	Dolomite, limestone, carbonate rock	Granite, gneiss, schist	Clay, shale, sand, gravel
Land cover	Rock, grassland	Deciduous and mixed forest	Grassland, coniferous forest	Crop land, deciduous and mixed forest
Mean annual prec. (mm/yr)	1025	1704	741	647
Mean annual flood (m^3/s)	33	73	64	16
Mean runoff (m^3/s)	4.13	4.51	5.37	1.05

the runoff coefficient is right skewed with a median of 0.17. The skewness implies that large runoff coefficients are rare but do occur occasionally. 170 events have been identified for this catchment. The Wulka at Schützen am Gebirge catchment is the driest catchment of this set and is located in the east of Austria close to the Hungarian border (Fig. 4d). It exhibits the smallest direct runoff depths of the four catchments. Most of the runoff coefficients are less than 0.1 and the median is 0.04. Runoff response is rather flashy and episodic which has produced the largest number of events identified out of the four catchments presented here (198 events).

The runoff coefficients of the four catchments differ vastly. The driest catchment has the smallest runoff coefficients while the wettest catchment has the largest runoff coefficients. The differences are apparent both in the median runoff coefficients as well as in the extremes. The 90% quantiles, for example, give values of 0.60, 0.82, 0.46 and 0.18 for the Ritzenried, Lunz, Zwettl and Schützen catchments, respectively. For the two wet catchments (Ritzenried and Lunz) no runoff coefficients less than 0.1 have been observed, but nearly 10% of the runoff coefficients in Ritzenried and 30% in Lunz are larger than 0.7.

Spatial variability — soils and climate

The differences in the distributions of runoff coefficients illustrated above for the four example catchments are representative of different regions in Austria and it is clear that they must have hydrological causes. They can be either due to differences in the rainfall forcing and climatic conditions, or due to differences in the catchment structure including soil type and land use, or both. To analyse these effects, we have classified all catchments by soils/land use and climate. The effect of soils and land use has been indexed here by the SCS curve number (US-SCS, 1972; Dingman, 1994, p. 391). The SCS method provides a procedure for estimating the curve number from soil type and land use and antecedent rainfall. Once the curve number is known it can be used to estimate event runoff depth from event rainfall depth for an ungauged catchment.

In this study we estimated the SCS curve number from soil and land use data. The digital soil map of Austria (ÖBG, 2001; Merz and Blöschl, 2004) was used to identify approximate estimates of the soil group. Lithosols, rendzinas, podzols and histozols, i.e. high infiltration capacity soils, were classified as soil group A; fluvisols, phaeozems and chernosems as soil group B; cambisols as soil group C; and luviosols with a relatively low infiltration capacity as soil group D. Although it is clear that the type of soil information available at the regional scale will not provide any of the small scale soil details found in catchments we do believe they represent the general regional patterns of soils characteristics to some extent.

The digital map of land use (Ecker et al., 1995) was used to assign land use or land cover. From both sources, the SCS curve numbers were inferred at a pixel scale of 250 m. These were averaged over each catchment area. The 337 catchments of the study area were then classified by the curve number.

Note that the curve number is used here as an index of the mean catchment response. Because of this, average antecedent rainfall conditions is assumed for all catchments. Also note that in this paper the curve numbers are used for grouping catchments only and no runoff coefficients have been calculated by this method. The distribution function of runoff coefficients of all catchments within a curve number group is shown in Fig. 6a. A curve number of 100 predicts that all the rainfall becomes runoff during an event while a curve number of 0 predicts no runoff. One would therefore expect large curve numbers to be associated with large runoff coefficients. This is however not fully borne out in the runoff coefficients derived from the runoff data. The catchments with curve numbers $CN < 25$ and $25 < CN < 50$ have very similar distributions of the runoff coefficient with a median of 0.18. Catchments with $CN > 75$ have larger runoff coefficients although the difference is not large (median of 0.20). The largest runoff coefficients occur in catchments with intermediate curve numbers of $50 < CN < 75$ (median of 0.28).

This is a counterintuitive result. We have therefore reclassified all catchments by climate in terms of the mean annual precipitation of each catchment. Mean annual precipitation has been estimated from 1091 raingauges over the period 1971 to 1997 and spatially interpolated using external drift kriging with catchment elevation as an auxiliary variable. The distributions of the runoff coefficients are shown in Fig. 6b. The lowest runoff coefficients occur in the driest catchments where mean annual precipitation is less than 700 mm/year (median of 0.11). As the mean annual precipitation increases so do the runoff coefficients. For catchments with mean annual precipitation of $700 < MAP < 1200$,

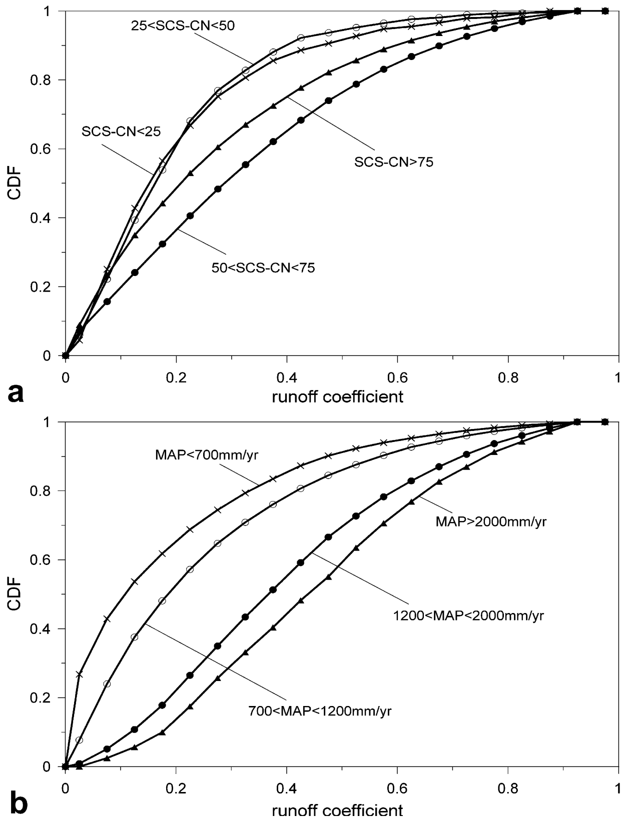

Figure 6 Distribution function of the event runoff coefficients of 337 catchments in Austria. Catchments have been stratified by (a) the SCS curve number; (b) mean annual precipitation.

1200 < MAP < 2000 and 2000 < MAP the median runoff coefficients are 0.18, 0.37 and 0.43, respectively. The largest runoff coefficients occur at the northern fringe of the Alps where mean annual precipitation is largest. The Lunz catchment in Figs. 4 and 5 is an example. These are mostly forested catchments while most of the lowland catchments have agricultural land use. For the catchments of the northern fringe of the Alps the SCS method predicts relatively small curve numbers as forest soils are usually highly permeable. While the soils permeability may be high in the catchments of question this seems to have little effect on the runoff coefficients. They seem to be controlled by the soil moisture status which tends to be much higher than in the drier lowland catchments. It appears that in this type of climate and at that catchment scale, soil moisture status is a more important control on the statistical characteristics of the runoff coefficients than the soil type.

Spatio-temporal variability

To shed more light on the temporal variability of the runoff coefficients, Beta distributions have been fitted to the cumulative distribution functions of runoff coefficients of each catchment individually. In the Beta probability density distribution

$$f(x|\alpha,\beta) = \frac{1}{B(\alpha,\beta)} x^{\alpha-1}(1-x)^{\beta-1} \quad \text{for } 0 < x < 1,\ \alpha > 0,\ \beta > 0 \tag{5}$$

with

$$B(\alpha,\beta) = \int_0^1 x^{\alpha-1}(1-x)^{\beta-1}\,dx = \frac{\Gamma(\alpha)\Gamma(\beta)}{\Gamma(\alpha+\beta)},$$

x is the event runoff coefficient and the α, β are the parameters. The cumulative distribution function of Eq. (5) has been fitted in the x domain by minimising the root mean squared differences. The results are shown in Table 2 and in Fig. 7. The catchments have been classified into wet and dry catchments according to their mean annual precipitation (greater or smaller than 1200 mm/yr) and, for each catchment, the events have been classified by the event rainfall depth including snowmelt. Small events were considered those where event rainfall depth including snowmelt was between 10 and 80 mm, large events were considered those were it was more than 80 mm. Table 2 suggests that the Beta distribution provided an excellent fit to the empirical distributions of the runoff coefficients. The root mean square errors were typically on the order of 0.01 for events with rainfall depths including snowmelt between 10 and 80 mm and 0.03 for events larger than 80 mm. The larger root mean square errors seems to be mainly related to the smaller number of events for the large event class. It may also be related to generally larger mean runoff coefficients in this class. In the dry catchments the β

Table 2 Parameters α, β of a Beta distribution and goodness of fit (root mean square error *rmse*) as well as statistical moments estimated from the distribution function of event runoff coefficients for each catchment

	Median						Number of catchments	Total number of events
	α	β	rmse	Mean	SD	Skewness		
10 < rain < 80 mm								
MAP < 1200 mm/yr	1.24	4.07	0.010	0.24	0.17	1.24	239	30,309
MAP > 1200 mm/yr	2.18	3.26	0.008	0.41	0.19	0.58	98	16,069
rain > 80 mm								
MAP < 1200 mm/yr	4.05	6.93	0.033	0.33	0.14	0.35	239	1038
MAP > 1200 mm/yr	4.61	4.54	0.025	0.49	0.14	0.16	98	1388

Median values of two catchment groups (mean annual precipitation less than or larger than 1200 mm) are given in this table. Events have been stratified by event rainfall depth including snowmelt (top: between 10 and 80 mm; bottom: more than 80 mm).

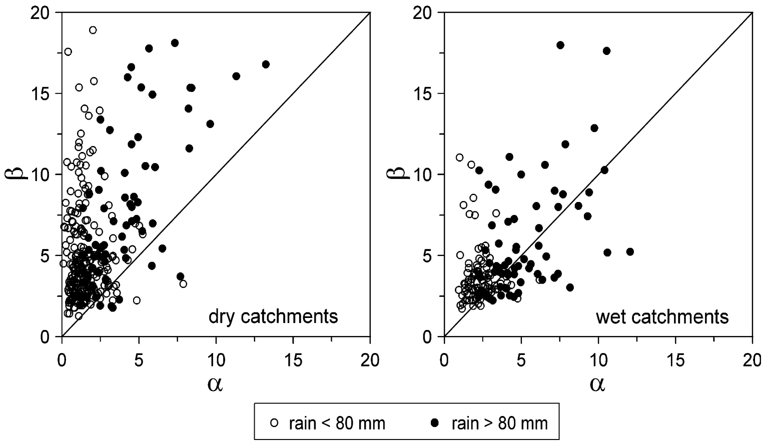

Figure 7 Parameters of a beta distribution fitted to the distribution of event runoff coefficients for 337 catchments in Austria. Catchments have been stratified by mean annual precipitation MAP (dry catchments: MAP < 1200 mm; wet catchments: MAP > 1200 mm). Events have been stratified by rainfall depths (including snowmelt) smaller/larger than 80 mm.

parameters are usually much larger than the α parameters which means that the distributions are highly skewed to the right. This is particularly the case for the small events in the dry catchments where the median of α is 1.2 while the median of β is 4.1. For these events the α values are rarely larger than 5 while the β values range up to 20. This is consistent with small average runoff coefficients (on the order of 0.2 see Table 2). For the larger events in the dry catchments the α parameter tends to increase which is consistent with a somewhat more uniform distribution and larger averages (see Table 2). In contrast, in the wet catchments, the α and β parameters are of the same order of magnitude particularly for the large events where both parameters range around 4.5.

The parameters of the Beta distributions of the runoff coefficients have now been regionally mapped and compared with the climatic regions in Austria. Interestingly, both the α and β parameters tend to be organised along similar patterns as the main climatic regions. Six regions were identified manually that are approximately homogeneous in terms of the Beta parameters of the runoff coefficient distribution. The region number is indicated in Fig. 8 for each catchment. The Beta parameters, classified by region, are shown in Fig. 9 and the median values for each region are given in Tables 3 and 4.

Region 1 (termed alpine region) covers the Alps in the west of Austria. Here, most events occur during summer when runoff is high because of snow and glacier melt. In these catchments, runoff coefficients tend to be rather high. The main reason seems to be that snow and ice melt increase antecedent soil moisture. For large events, α is somewhat larger and β is much larger than for small events which translates into a more skewed distribution. Region 2 (termed southern alpine region) covers the high alpine catchments in East Tyrol and along the river Gail in the very south of Austria. Similar to region 1, snowmelt is important but some of the large events result from storms that approach from the south and are of Mediterranean origin.

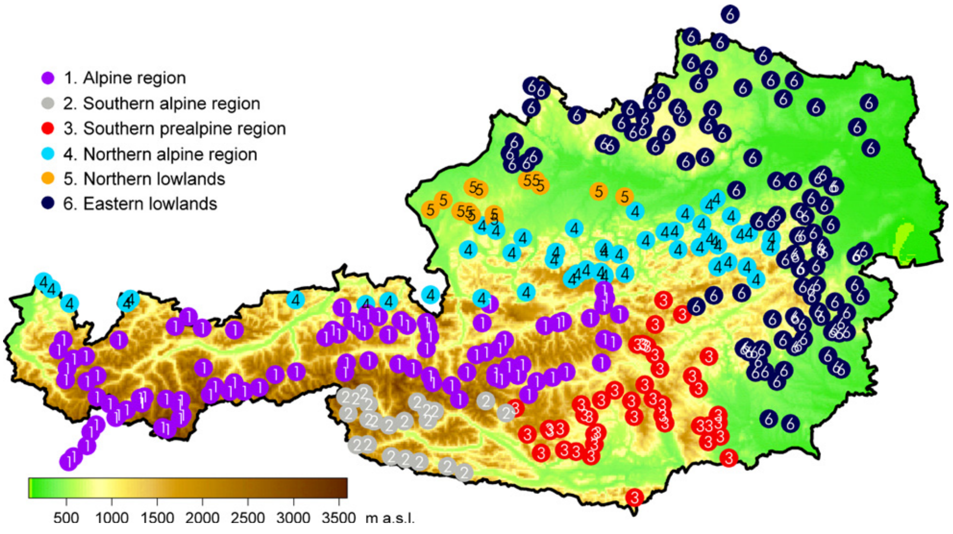

Figure 8 Location of regions with similar distribution functions of event runoff coefficients. Numbers have been plotted at the location of each gauged catchment and refer to the group numbers as of Fig. 9.

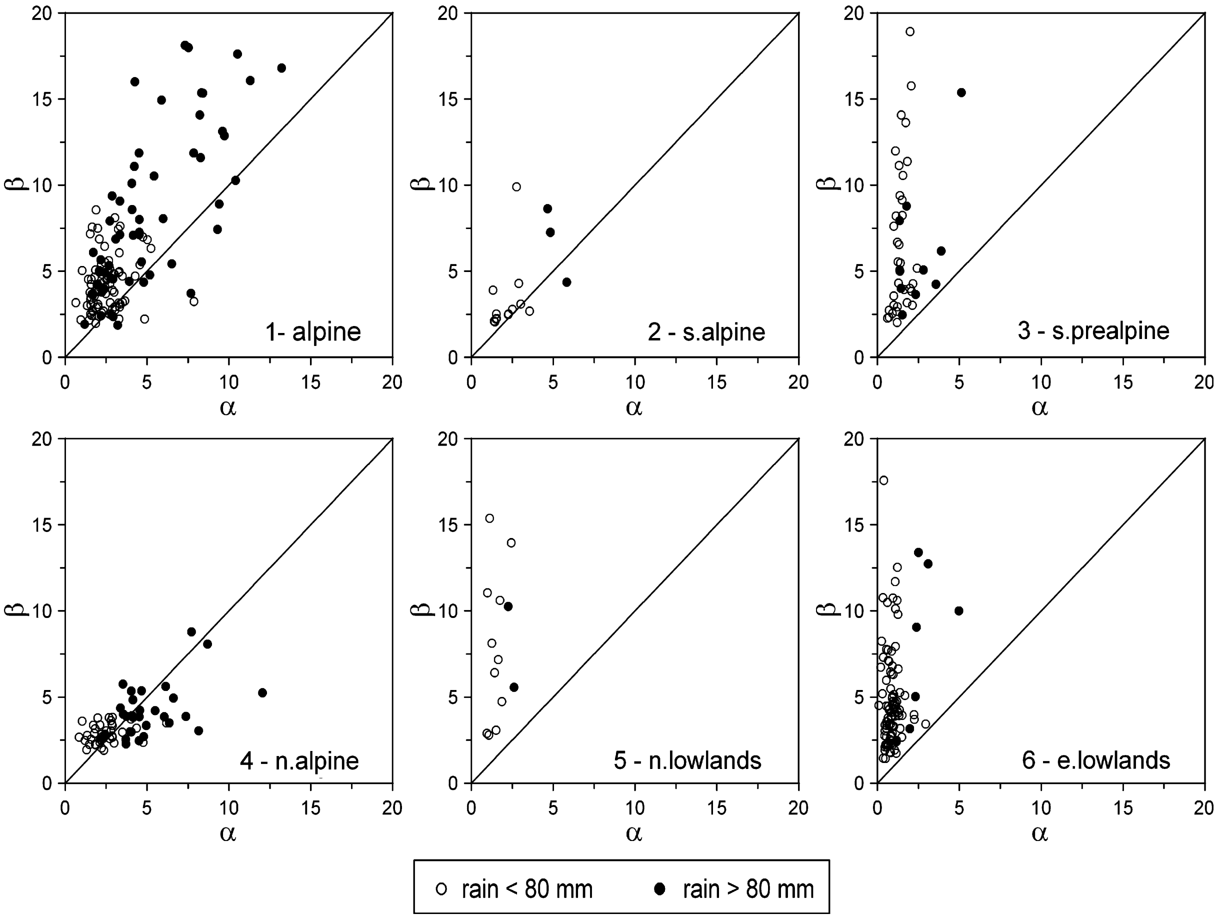

Figure 9 Parameters of a beta distribution fitted to the distribution of event runoff coefficients for 337 catchments in Austria. Catchments have been stratified into regions as of Fig. 8.

The runoff coefficients are higher, on average, than for region 1 and less skewed. Region 3 (termed southern prealpine region) covers the south-east of Austria which consists of lower alpine terrain. Rainfall is significantly lower than in regions 1 and 2 and snow processes are less important. Runoff coefficients are smaller but the skewness is higher, particularly for the small events where β can be up to 20 while α is only 2. However, α is almost never smaller than 1 which means that very small runoff coefficients occur rarely. Region 4 (termed northern alpine region) is on the northern fringe of the central Alps. This is the region of highest rainfall in Austria because of orographic effects. The dominant soil type is rendzina and the region is densely forested. In this region the runoff coefficients are largest with median means of 0.42 (small events) and 0.54 (large events). The α and β parameters are similar for both small and large events indicating that the distribution is almost symmetric. Region 5 (termed northern lowlands) in the north-west of Austria is rather flat and the runoff coefficients are small. Luvisols prevail in these catchments and land use is mainly

Table 3 Parameters α, β of a Beta distribution and goodness of fit (root mean square error *rmse*) as well as statistical moments estimated from the distribution function of event runoff coefficients for each catchment

Region	Median						Number of catchments	Total number of events
	α	β	rmse	Mean	SD	Skewness		
1— Alpine	2.25	3.82	0.015	0.40	0.19	0.84	95	8549
2 — Southern alpine	1.61	2.79	0.018	0.42	0.20	0.60	21	1337
3 — Southern prealpine	1.34	4.94	0.011	0.23	0.16	1.53	42	4961
4 — Northern alpine	2.22	2.87	0.006	0.42	0.20	0.36	51	10,407
5 — Northern lowlands	1.63	7.19	0.004	0.20	0.13	1.22	15	3488
6 — Eastern lowlands	0.85	4.12	0.006	0.11	0.16	1.61	113	17,636
All catchments	1.54	3.79	0.010	0.31	0.18	1.05	337	46,378

Median values of six climatic regions are given in this table. Events with rainfall depths including snowmelt between 10 and 80 mm.

Table 4 As Table 3 but for event rainfall depths including snowmelt larger than 80 mm

Region	Median						Number of catchments	Total number of events
	α	β	rmse	Mean	SD	Skewness		
1— Alpine	4.53	7.67	0.030	0.39	0.13	0.35	95	1137
2 — Southern alpine	4.82	6.99	0.034	0.45	0.15	0.23	21	126
3 — Southern prealpine	2.33	5.08	0.040	0.30	0.15	0.35	42	165
4 — Northern alpine	4.66	4.00	0.028	0.54	0.16	-0.05	51	814
5 — Northern lowlands	2.43	7.92	0.038	0.27	0.10	0.72	15	54
6 — Eastern lowlands	2.51	9.53	0.033	0.23	0.15	0.34	113	130
All catchments	4.25	5.46	0.032	0.37	0.14	0.29	337	2426

agricultural. Region 6 (termed eastern lowlands) is the driest part of Austria in the east and north east. Most of the catchments are rather flat. Land use is agricultural and soils are mainly chernosems and phanozems as well as cambisols and luvisols. Much of the geology is of tertiary and quaternary origin. The α parameters in region 6 are very small and the β parameters are significantly larger indicating low average runoff coefficients and highly skewed distributions. For the large events, α is larger than for the small events indicating that the runoff coefficients tend to be larger and the distribution is less skewed. Clearly, in this type of climate most of the event precipitation infiltrates during an event and it is only in rare occasions that runoff coefficients are large, either due to large antecedent soil moisture or large event rainfall, or both.

Temporal variability — rainfall and antecedent soil moisture

To isolate the effects of event rainfall and antecedent soil moisture each of the regions has been examined in more detail. As an example, results from region 4 (the wettest region with the largest runoff coefficients) and region 6 (the driest region with the smallest runoff coefficients) are shown here. As each of the regions is analysed individually, it is possible to separate the temporal effects of storms and antecedent soil moisture from the regional effects of climate, soils and geology.

In Fig. 10a the runoff coefficients of the two regions have been classified by the event rainfall including snowmelt. In both regions, the runoff coefficients increase significantly with event rainfall. In region 4, the median runoff coefficient of small storms (event rainfall < 80 mm) is 0.42 while for the larger storms it is 0.54. In region 6, the median runoff coefficient of small storms is 0.11 while for the larger storms it is 0.23. It is interesting to note that the difference in the runoff coefficients between the regions is much larger than the difference between the storms of different sizes for a given region. The event rainfall depth classes have also been varied (not shown here) and gave consistently smaller differences than those between regions.

In Fig. 10b the runoff coefficients of the two regions have been classified by antecedent rainfall including snowmelt over the previous 10 days. This is a measure of the soil moisture state of the catchment. Choice of this measure has been motivated by the antecedent soil moisture index of five day rainfall used in the SCS CN method although it is clear that it does not fully capture all complexities of the catchment water balance. For Austrian conditions, 10 days seem to be more representative than five days for indexing soil moisture. In both regions, the runoff coefficients increase with antecedent rainfall as would be expected. In region 6, the median runoff coefficient for dry and intermediate moisture conditions (antecedent rainfall < 90 mm) is 0.11 while for wet conditions (antecedent rainfall > 90 mm) it is 0.21. In region 4, the median runoff coefficient for dry and intermediate moisture conditions is 0.38 while for wet conditions it is 0.48. Again, the differ-

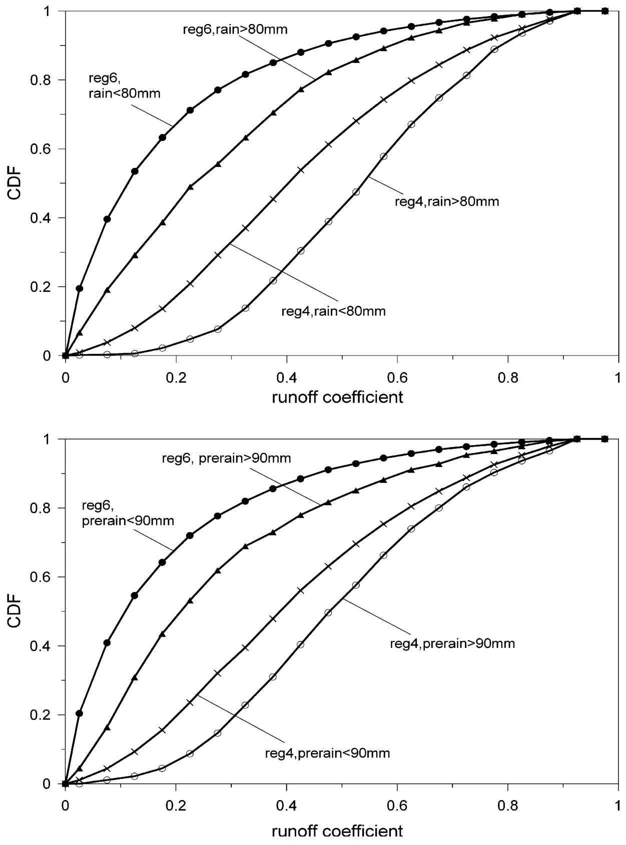

Figure 10 Distribution functions of the event runoff coefficients for the catchments in regions 4 and 6 (see Fig. 8). Top: Effect of event rainfall depths (including snowmelt). Bottom: Effect of antecedent rainfall depths (including snowmelt) over 10 days.

ence in the runoff coefficients between the regions is much larger than between the storms of different antecedent conditions for a given region.

Flood types

The final step in the analysis was to relate the runoff coefficients to flood process types to further examine process controls. Merz and Blöschl (2003) identified types of causative mechanisms of floods which were used here. The types were long-rain floods, short-rain floods, flash floods, rain-on-snow floods and snow-melt floods. They used 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. Based on these indicators and diagnostic regional plots they identified the process types of 11,518 maximum annual flood peaks in 490 Austrian catchments. 43% of the flood peaks were long-rain floods, only 3% were snow-melt floods and the relative contribution of the types changed with the flood magnitude. There were also pronounced spatial patterns in the frequency of flood type occurrence. For example, rain-on-snow floods most commonly occurred in northern Austria.

The two data sets (the runoff coefficient data set of this paper and the flood type data set of Merz and Blöschl (2003)) were now combined. The runoff coefficient data set contained most of the maximum annual flood events of the flood process type data set but a large number of smaller events of the runoff coefficient data was not part of the flood type data set. There were a total of 3032 events that existed in both data sets (1315 long-rain floods, 1009 short-rain floods, 69 flash floods, 593 rain-on-snow floods and 46 snow-melt floods). For these events the flood types of Merz and Blöschl (2003) were used to classify the runoff coefficients. The distribution functions of the runoff coefficients classified by flood type are shown in Fig. 11. There are very large differences between the flood types. The smallest runoff coefficients are associated with flash floods with a median of 0.15. These are flood events with limited spatial extent resulting from short rainfall bursts of convective origin. It should be noted that the median catchment size of this analysis is 265 km^2 while most of the convective storms will have a much smaller spatial extent. If smaller catchments (on the order of hectares or a few square kilometres) were examined one would significantly larger runoff coefficients (Gutknecht, 2003). It is likely that for some of the flash flood events of this data set the catchment is not fully covered by the storm and runoff generation is at least partly due to Hortonian mechanisms. The second smallest runoff coefficients are associated with short-rain floods with a median of 0.36. These are events that mainly occur in the south of Austria as a result of short storms that have significant spatial extent. Slightly larger runoff coefficients (median of 0.38) are produced by long-rain floods which result from synoptic or frontal type storms that often cover an area up to several thousands of square kilometres and can last over a few days. In these types of events, much of the catchment seems to wet up, so saturation excess overland flow may be an important runoff generation mechanism. Rain-on-snow events are associated with still larger runoff coefficients with a median of 0.48. This type of floods often occurs in the winter and it is apparently the increase of antecedent soil moisture due to snowmelt and rain falling on wet soils that causes the large runoff coefficients. The largest runoff coefficients are associated with snowmelt floods with a median of 0.63. Snowmelt usually occurs over a number of days with increasing snowmelt rates during this period as air temperatures increase and the snow gets gradually wetter. Over this period, the catchment wets up so that even relatively small melt rates can lead to flooding. Also, because the snow melt events usually extend over a couple of days the (direct) quickflow component tends to contain some of the more delayed water.

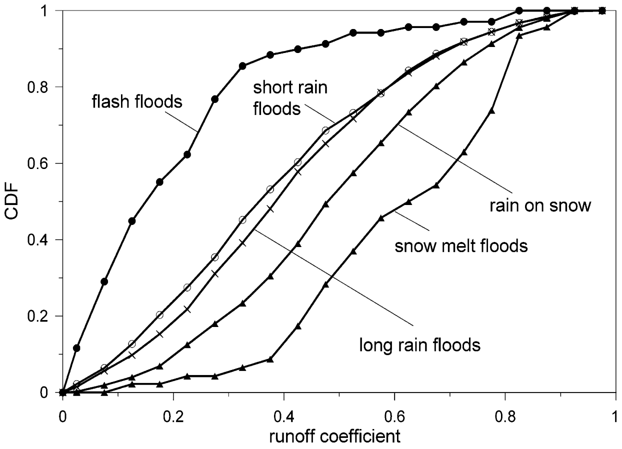

Figure 11 Distribution function of the event runoff coefficients for maximum annually floods in Austria stratified by the event type.

The differences between the flood types are also apparent in the extremes. Snowmelt floods almost never have small runoff coefficients and flash floods are almost never associated with large runoff coefficients.

Discussion and conclusions

The analyses indicated large regional differences in the runoff coefficients within Austria. In catchments where mean annual rainfall is high, runoff coefficients tend to be large and the distribution function for any one catchment is almost uniform. In dry catchments, the runoff coefficients tend to be small and they are highly skewed. Clearly, these differences in the distribution functions will have an effect on the flood frequency characteristics of the catchments. The Kamp catchment in northern Austria is an example of a relatively dry catchment. The runoff coefficients are usually small but larger runoff coefficients do occur such as during the 2002 flood when the flood peak was more than three times the second largest flood on record (Gutknecht et al., 2002). It would have been difficult to predict this flood from the observed flood frequency curve as the characteristics of the 2002 flood were different from those of the available flood sample, in particular from the previously observed runoff coefficients. In the catchments with larger runoff coefficients outliers may not be as extreme as in drier catchments.

The distribution functions of the runoff coefficients can be well represented by a Beta distribution. The parameters of this distribution exhibit spatial patterns that match six regions of Austria. These are climatic regions that exhibit characteristic runoff regimes. Gottschalk and Weingartner (1998) summarised the parameters of a Beta distribution of runoff coefficients for 17 Swiss catchments and grouped them according to the physiographic conditions of these catchments. The runoff coefficients of the Swiss high alpine catchments were smaller and more skewed than those in the Alpine region here (mean of 0.10 while the mean of this study was 0.40). The authors attributed the small runoff coefficients to the presence of permanent snow while here the effect of snow processes mainly seems to be in increasing antecedent soil moisture. The Swiss prealpine region is similar to the southern prealpine region here in terms of the distribution of runoff coefficients (mean of 0.33). The Swiss midlands had a mean of 0.16 and were highly skewed; the Swiss southern alpine region had a mean of 0.19 and was moderately skewed. They both fall in the range between the eastern lowlands and southern prealpine catchments here. It is interesting that Gottschalk and Weingartner (1998) interpreted the Swiss runoff coefficients mainly by topographic characteristics such as altitude and slope and to some degree by stream network density and geology. It appears that in Austria the main driver is the catchment water balance rather than topographic characteristics. The spatial patterns of median runoff coefficients (Merz et al., 2004, not shown here) are very similar to the spatial patterns of mean annual precipitation in Austria. Region 4 (the northern alpine region) gives the highest runoff coefficients. It does not contain the steepest catchments but those with the highest precipitation rates and, in particular, the highest mean annual precipitation. Persistent and frequent rainfall causes the soil moisture status of the catchments to be high during most of the time which increases the likelihood of an event to occur when the catchment is wet. This points to the very important effect of climate and the runoff regime on event runoff coefficients.

It is interesting to note that the difference in the runoff coefficients between the regions is much larger than between the storms of different sizes for a given region. The role of antecedent soil moisture is highlighted through these regional differences and is corroborated by other analyses in this paper. Antecedent soil moisture has been indexed by antecedent 10 day rainfall. Events with larger antecedent rainfall show significantly larger runoff coefficients than events with dryer initial conditions. The other analysis that corroborates the role of antecedent soil moisture are the runoff coefficients for different flood types. Interestingly, the largest runoff coefficients occur for the snowmelt events and the rain-on-snow floods. It should be noted that snowmelt has been taken into account in this analysis, so the larger runoff coefficients are not directly attributable to snowmelt contributions to the event but to an increase in initial soil moisture. Initial conditions are likely to affect runoff volume for most runoff generation types; in Hortonian runoff through reducing infiltration capacity, in saturation excess runoff through expanding contributing areas, and in macropore flow and subsurface stormflow through connecting preferential flow paths (Merz and Plate, 1997; Zehe and Blöschl, 2004). In most of the catchments of the study area runoff generation likely occurs by a mix of these mechanisms. Initial conditions are not always found to closely drive runoff response. There are examples in the literature where runoff volumes seem to be insensitive to antecedent soil moisture and mainly controlled by event precipitation. An example is the study of Kostka and Holko (2003) who analysed runoff response of a mountainous catchment in Slovakia. They suggested that the lack of sensitivity of runoff response to soil moisture is related to the role of the riparian zone in runoff generation.

The soil moisture status in the catchments of the study area is highly seasonal, similar to many catchments around the world. The main drivers here are snow processes in winter and spring, and evaporation and transpiration in summer, along with the seasonality of precipitation (Merz and Blöschl, 2003). Intra-annual climate variability strongly impacts upon flood frequency characteristics in a direct way through the seasonal variability of storm characteristics, and indirectly through the seasonality of rainfall and evapotranspiration which then affect the antecedent catchment conditions for individual storm events. Sivapalan et al. (2005) proposed a quasi-analytical derived flood frequency model that is able to account for both types of seasonalities. They showed that it is the interplay of the event and seasonal scales that control flood frequency behaviour. Kohnová and Szolgay (2003) discuss a similar interplay between the flood regime and its controls in the context of snowmelt induced floods in Slovakia.

While climate and antecedent soil moisture seemed to be very important in controlling the runoff coefficients, 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. The tables of the SCS curve number method do not seem to apply to the catchments of the study area even though they are widely used in many countries. The main contrast in the spatial patterns of the SCS curve number was due to the patterns of forest and agricultural land with small curve numbers in the forested catchments while the runoff coefficients derived from the runoff data were largest in those catchments. However, any other classification by land use and land cover would have a similarly low predicitive power. Forest cover is usually thought to affect runoff generation by two main mechanisms in temperate climates (Andréassian, 2004; Brown et al., 2005). The first is to enhance interception due to large leaf areas as compared to grass land or agricultural land which may be important for small events. The second mechanism are generally larger permeabilities of forest soils which should be important for both small and large events. Results of this study suggest that other mechanisms may mask these effects, and land use and land cover do not seem to be good predictors of runoff coefficients at the catchment scale. The soil characteristics were derived from a regional scale data set and hydraulic characteristics estimated from this type of data are notoriously unrepresentative of catchment scale processes (Blöschl, 2005). While this is the type of information available in many practical studies it is likely that more detailed soils data that include hydraulic characteristics will have better explanatory power of the runoff coefficients. Perhaps more importantly, it should be noted that the catchments examined here were all medium sized to large (larger than 80 km^2). Some of the land use and soil characteristics are likely to average out over this catchment size. Also, Cerdan et al. (2004) noted that the spatial arrangement of areas of a given land use within a catchment will be important for runoff coefficients at the catchment scale. The low correlation of runoff coefficients to land use and soils found in this study hence seems to be related to scale effects. Once one moves to smaller scales, soils and land use are likely to become more important as illustrated by numerous plot scale studies. FAO (2000, p. 2) noted: ''As a general rule, impacts of land use activities on hydrological and sediment-related processes can only be verified at smaller scales (up to some tens of square kilometres) where they can be distinguished from natural processes and other sources of degradation''. It is clear that at the plot scale, land use and soil characteristics may have a dramatic effect on the runoff coefficients, but for the catchments scales examined here, the aggregate effect seems to be small. The main controls on event runoff coefficients are the climate and the runoff regime through the seasonal catchment water balance and hence antecedent soil moisture in addition to event characteristics.

There exist a number of logical extensions of the work reported in this paper. First, the results from the event scale analysis could be compared to an analysis based on soil moisture accounting schemes. It is likely that the soil moisture accounting models provide more representative antecedent soil moisture states than those of the antecedent rainfall indices currently in use. Second, it would be good to use the runoff coefficient data base obtained here for developing a model that is able to predict runoff coefficients for ungauged catchments in Austria and similar climates.

Acknowledgements

The authors thank the Austrian Ministry of Agriculture, Forestry, Environment and Water Management (Project: Analysis of event runoff coefficients at the regional scale), the Austrian Academy of Sciences (APART [Austrian Programme for Advanced Research and Technology] – fellowship), the Austrian Science Foundation (FWF), project number P14478-TEC and the Marie Curie Fellowship of the European Community programme HUMAN POTENTIAL under contract number HPMF-CT-2002-01872 for financial support. We also thank the Austrian Hydrographic Service (HZB) for providing the hydrographic data.

Appendix. Estimation of the characteristic time scale t'_c of runoff dynamics

To assist in event separation, a characteristic time scale t'_c of the runoff dynamics of each runoff peak was estimated first. A number of typical hourly catchment rainfall time series were transformed to runoff q_i^* using a linear reservoir with storage parameter t_c assuming that all of rainfall becomes runoff. The generated runoff time series were then smoothed by a filter

$$q_i^c = q_{i-1}^c + a_c \cdot (q_i^* - q_{i-1}^c), \tag{A.1}$$

$$a_c = 1 - e^{-\frac{\Delta t}{k_c}}, \tag{A.2}$$

where q_i^c is the smoothed runoff at time i, q_i^* is the original runoff at time i and Δt is the sampling interval of 1 h. The parameter a_c is a function of the storage parameter k_c (Eq. (A.2)). The runoff times series were filtered forward (Eq. (A.1)) and backward. The maximum annual flood peaks were then extracted both from the smoothed (q_n^c) and original q_n^* runoff time series for each year n. The maxima from the original series were always larger than those from the smoothed series. The average of q_n^*/q_n^c for each catchment over n years (termed q^*/q^c) was then parameterised by fitting for each catchment

$$\frac{q^*}{q^c} = 1 + \beta_1 \left(\frac{k_c}{t_c}\right)^{\beta_2}. \tag{A.3}$$

The coefficients β_1 and β_2 slightly varied between catchments and were $\beta_1 = 0.95$ and $\beta_2 = 0.85$ on average over the catchments. The coefficients were insensitive to the choice of t_c. Eq. (A.3) reflects the temporal variability of rainfall within each event and the runoff response using a linear reservoir with time constant t_c. Eq. (A.3) was now used to estimate the time scale t_c for each peak in the entire data set by filtering the runoff time series and comparing the peaks from the filtered and the unfiltered time series. A visual inspection of events showed that for the Austrian case study it is advantageous to transform the temporal scale by

$$t'_c = \left(\frac{t_c}{t_\gamma}\right)^{\gamma}, \tag{A.4}$$

where $\gamma = 0.4$ and $t_\gamma = 24$, and to limit t'_c to values between 6 and 60 h.

References

Andréassian, V., 2004. Waters and forests: from historical controversy to scientific debate. J. Hydrol. 291 (1–2), 1–27.

Blöschl, G., 2005. Rainfall-runoff modeling of ungauged catchments. In: Anderson, M.G. (Managing Editor), Article 133 in: Encyclopedia of Hydrological Sciences. J. Wiley & Sons, Chichester, pp. 2061–2080.

Brown, A.E., Zhang, L., McMahon, T.A., Western, A.W., Vertessy, R.A., 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. J. Hydrol. 310 (1–4), 28–61.

Cerdan, O., Le Bissonnais, Y., Govers, G., Leconte, V., van Oost, K., Couturier, A., King, C., Dubreuil, N., 2004. Scale effects on runoff from experimental plots to catchments in agricultural areas in Normandy. J. Hydrol. 299, 4–14.

Chapman, T.G., Maxwell, A.I., 1996. Baseflow separation – comparison of numerical methods with tracer experiments. I.E. Aust. Natl. Conf. Publ 96/05, pp. 539–545.

Dingman, S.L., 1994. Physical Hydrology. Macmillan, New York, 575pp.

Dos Reis Castro, N.M., Auzet, A.-V., Chevallier, P., Leprun, J.-C., 1999. Land use change effects on runoff and erosion from plot to catchment scale on the basaltic plateau of Southern Brazil. Hydrol. Process. 13, 1621–1628.

Duan, Q., Sorooshian, S., Gupta, V.K., 1992. Effective and efficient global optimization for conceptual rainfall-runoff models. Water Resour. Res. 28, 1015–1031.

Ecker, R., Kalliany, R., Steinnocher, K., 1995. Fernerkundungsdaten für die Planung eines Mobilfunknetzes. Österr. Zeitschr. f. Vermessung Geoinformation 83, 14–25.

FAO, 2000. Land-water linkages in rural watersheds – Electronic workshop. 18 September–27 October 2000. Conclusions and recommendations. Food and Agriculture Organization of the United Nations, Rome, Italy.

Gottschalk, L., Weingartner, R., 1998. Distribution of peak flow derived from a distribution of rainfall volume and runoff coefficient, and a unit hydrograph. J. Hydrol. 208, 148–162.

Grayson, R.B., Argent, R.M., Nathan, R.J. McMahon, T.A., Mein, R.G., 1996. Hydrological recipes – estimation techniques in Australian hydrology. Cooperative Research Centre for Catchment Hydrology, Department of Civil Engineering, Monash University Clayton, Victoria, Australia.

Grebner, D., 1995. Klimatologie und Regionalisierung starker Gebietsniederschläge in der nordalpinen Schweiz. Zürcher Geographische Schriften 59, ETH Zürich.

Grebner, D., Roesch, Th., 1998. Flächen-Mengen-Dauer-Beziehungen von Starkniederschlägen und mögliche Niederschlagsgrenzwerte in der Schweiz. Schlussbericht NFP 31 vdf, ETH Zürich.

Gutknecht, D., 2003. Extreme runoff events in small catchments – the need for a proper modelling strategy for early warning systems. In: Zschau, J., Küppers, A.N. (Eds.), Early Warning Systems for Natural Disaster Reductions. Proc. EWC'98. Springer, Berlin, pp. 265–269.

Gutknecht, D., Reszler, Ch., Blöschl, G., 2002. Das Katastrophenhochwasser vom 7. August 2002 am Kamp – eine erste Einschätzung (The August 7, 2002 – flood of the Kamp – a first assessment). Elektrotech. Informationstechnik 119 (12), 411–413.

Kohnová, S., Szolgay, J., 2003. Regional estimation of the index flood and the standard deviation of the summer floods in the Tatry mountains. J. Hydrol. Hydromech. 51 (4), 241–255.

Kostka, Z., Holko, L., 2003. Analysis of rainfall-runoff events in a mountain catchment. In: Holko, L., Miklánek, P. (Eds.), Interdisciplinary Approaches in Small Catchment Hydrology: Monitoring and Research, IHP-VI Technical Documents in Hydrology no. 67. UNESCO, Paris, pp. 19–25.

Lutz, W., 1984. Berechnung von Hochwasserabflüssen unter Anwendung von Gebietskenngrößen. Mitteilung Nr. 24 des Instituts für Hydrologie und Wasserwirtschaft, Universität Karlsruhe.

Merz, R., Blöschl, G., 2003. A process typology of regional floods. Water Resour. Res. 39 (12), 1340. doi:10.1029/2002WR001952.

Merz, R., Blöschl, G., 2004. Regionalisation of catchment model parameters. J. Hydrol. 287, 95–123.

Merz, B., Plate, E., 1997. An analysis of the effects of spatial variability of soil and soil moisture on runoff. Water Resour. Res. 33 (12), 2909–2922.

Merz, R., Blöschl, G., Parajka, D., Reszler, Ch., 2004. Analyse regionaler Ereignisabflussbeiwerte in Österreich. Technischer Bericht an das BM für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft Wien, Institut für Hydraulik, Gewässerkunde und Wasserwirtschaft TU Wien.

Naef, F., 1993. Der Abflusskoeffizient: einfach und praktisch? In: Aktuelle Aspekte in der Hydrologie, Zürcher Geographische Schriften, Heft 53, Verlag Geographisches Institut ETH Zürich, pp. 193–199.

ÖBG, 2001. Bodenaufnahmesysteme in Österreich. Mitteilungen der Österreichischen Bodenkundlichen Gesellschaft, Heft 62.

Parajka, J., Merz, R., Blöschl, G., 2005. A comparison of regionalisation methods for catchment model parameters. Hydrol. Earth Syst. Sci. – Discussions 2 (2), 509–542, SRef-ID: 1812-2116/hessd/2005-2-509.

Piock-Ellena, U., Blöschl, G., 1998. Abflußtypen-Klassifizierung als Basis für die Regionalisierung von Hochwässern. Technischer Bericht an die Österreichische Akademie der Wissenschaften (HÖ-12/97), Institut für Hydraulik, Gewässerkunde und Wasserwirtschaft TU Wien.

Sevruk, B., Paulais, M., Roulet, Y.-A., 1998. Correction of precipitation measurement using fresh snow as reference. In: Proceedings of the WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation, TECO-98. WMO/TD-No. 877, Geneva, Switzerland, pp. 349–352.

Sherman, L., 1932. Streamflow from rainfall by unit hydrograph method. Engineering News Records 108, Chicago, pp. 501–505.

Sivapalan, M., Blöschl, G., Merz, R., Gutknecht, D., 2005. Linking flood frequency to long-term water balance: incorporating effects of seasonality. Water Resour. Res. 41 (6), W06012. doi:10.1029/2004WR003439.

Tallaksen, L.M., 1995. A review of baseflow recession analysis. J. Hydrol. 165, 349–370.

US-SCS, 1972. National Engineering Handbook Section 4 Hydrology. US Department of Agriculture.

Zehe, E., Blöschl, G., 2004. Predictability of hydrologic response at the plot and catchment scales: role of initial conditions. Water Resour. Res. 40. doi:10.1029/2003WR002869.