Nat Hazards (2008) 46:53–72
DOI 10.1007/s11069-007-9181-7

ORIGINAL PAPER

National flood discharge mapping in Austria

Ralf Merz · Günter Blöschl · Günter Humer

Received: 15 May 2007 / Accepted: 9 September 2007 / Published online: 8 January 2008

Abstract This article presents the approach and the results of a study in which 30, 100 and 200 year return period flood discharges were estimated for 26,000 km of Austrian streams. Three guiding principles were adopted: combination of automatic methods and manual assessments by hydrologists to allow speedy processing and account for the local hydrological situation; combination of various sources of information including flood peak samples, rainfall data, runoff coefficients and historical flood data; and involvement of the Hydrographic Services to increase the accuracy and enhance the acceptance of results. The flood discharges for ungauged catchments were estimated by the Top-kriging approach with manual adjustment to the local flood characteristics. The adopted combination approach proved to be very efficient both in terms of the project time required and in terms of the accuracy and acceptability of the estimated flood discharges of given return periods.

Keywords Flood · Hazard mapping · Regionalisation · Flood frequency · Ungauged catchments

1 Introduction

Austria has experienced major floods in the last years, notably the flood event in August 2002 with a total damage of more than three billion Euro. More than 100,000 people have been affected by this flood through damage to housing or other property. The 2002 flood was the catalyst for a number of flood risk related activities. One of them is a national flood mapping project known as HORA (HOchwasserRisikoflächen Austria—Flood risk zones

---

R. Merz (✉) · G. Blöschl
Institute for Hydraulic and Water Resources Engineering, Vienna University of Technology,
Karlsplatz 13/222, Vienna 1040, Austria
e-mail: merz@hydro.tuwien.ac.at

G. Humer
Ingenieurbüro DI Günter Humer—Ingenieurbüro f. Kulturtechnik und Wasserwirtschaft,
4682 Geboltskirchen 70, Austria
e-mail: office@ib-humer.at

in Austria). The project was motivated by two main objectives. The first was an interest of the Austrian Association of Insurance Companies (VVO) to obtain a tool for premium estimation as floods have recently become insurable in Austria. The second was an interest of the Austrian Ministry of Agriculture, Forestry, Environment and Water Management to comply with the recent flood directive of the European Community (EU 2006) which requires the mapping of flood risk zones and their public access for the entire stream network until 2013.

The flood mapping project related to a total of 26,000 km of streams in Austria and consisted of three parts: estimation of flood discharges of a given return period; estimation of inundation areas by hydraulic models based on these discharges; and development of an Internet application to offer public access to the flood hazard maps. This article is concerned with the first step. Specifically, the aim was to estimate the flood discharges associated with 30, 100 and 200 year return periods for a total of about 10,000 river cross sections.

A number of countries have recently performed similar flood hazard mapping projects. Ireland, for example, has a National flood hazard mapping site on http://www.floodmaps.ie/. Hall et al. (2005) used existing Indicative Floodplain Maps (IFMs) to estimate potential flood damage in England and Wales. Bradbrook et al. (2005) derived national flood plain maps for 80,000 km of rivers in England and Wales. Flow estimates were derived by automatic Flood Estimation Handbook techniques (IH 1999) and a 2-dimensional raster-based floodplain model was used to produce the flood outline. Rodda (2005) developed a flood risk model for the Czech Republic. They generate synthetic flood events directly from flow data through a judgement-based approach using selected historical flood events from 1935.

To account for the specific requirements of the Austrian flood mapping project a new approach was developed which is presented in this article.

2 Project design

Estimation of the *T*-year floods was organised into three steps: Data pre-processing; flood estimation for gauged catchments (i.e. catchments where discharge data are available); and flood estimation for ungauged catchments (Fig. 2). As flood estimation in a country as diverse as Austria poses particular challenges, a number of guiding principles were adopted both for the gauged and ungauged cases.

2.1 Combination of automatic methods and manual assessments by hydrologists

Two categories of flood frequency estimation approaches exist. The first category involves automatic methods, such as parameter estimation from flood peak data for gauged catchments and regional regressions for ungauged catchments. While these methods can be readily applied to a large number of catchments, they tend not to be able to account for local particularities of catchments (Merz and Blöschl 2005). The second approach is normally used for design and consists of estimating flood frequency on a case by case basis, based on all available information in a particular catchment (including rainfall, flood hydrographs, etc.). This method can account for local effects, e.g. through use of 'soft information' but it is labour intensive and is hardly feasible to perform for 10,000 catchments. In this project, a combined iterative approach was adopted, where automatically produced estimates were manually assessed and, as needed, adjusted. For the gauged catchment case, the statistical moments of the local flood data are estimated automatically and then adjusted by expert judgement based on auxiliary information. For the ungauged catchment case the flood moments are estimated automatically by a regionalisation method from the flood data in a region, and pilot points are set to adjust the regional patterns manually based on auxiliary information.

2.2 Combination of various sources of information

Large-scale flood hazard mapping projects sometimes use catchment area alone as a surrogate for flood discharge (e.g. Kron and Willems 2002). In a country that is hydrologically as diverse as Austria, this assumption can be grossly in error. As indicated in Fig. 1, the 100 year flood discharges in Austria, for a given catchment size, vary by three orders of magnitude. Clearly, more accurate estimates than that are needed for flood hazard mapping. The standard method of estimating flood frequency for gauged catchments consists of analysing the maximum flood discharges in each year (Bobée and Rasmussen 1995). However, peak discharges are prone to measurement errors, including problems with rating curves, and flood flows may bypass the gauging station. Clustering of events in time is a general property of floods (Mandelbrot and Wallis 1968), so the observation window may not be representative of the population of floods of interest. Also, non-stationarities due to land use change and river works may exist and the record lengths are usually not as long as would be required on statistical ground (e.g. at least one-third of the return period; DVWK 1999). Flood frequency estimation based on the local flood peak data alone may hence not render the accuracy desired for the flood hazard mapping. Similarly, the errors of standard regionalisation methods tend to be large (Merz and Blöschl 2005). For this reason additional information is used here to expand the information beyond the flood peak data. Three types of information expansion are considered: temporal, spatial and causal. Temporal information expansion extends the flood records further into history. Spatial information expansion uses flood information of neighbouring catchments. Causal information expansion explores the flood generation processes. These pieces of information include both quantitative and qualitative (soft) information.

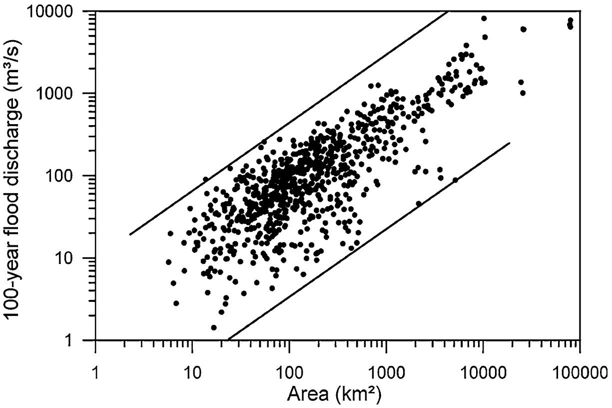

Fig. 1 Hundred year floods of 698 stream gauges in Austria plotted versus catchment area. For a given catchment size, the discharges vary by three orders of magnitude

2.3 Involvement of Hydrographic Services—acceptance of results

The aim of the project was to obtain the flood discharge estimates that are both scientifically sound and acceptable to the local Hydrographic Services and the River Authorities. For acceptability, it is important to use those pieces of information in the estimation process that are available to the local authorities. Local information includes evidence of historic floods, the local hydrogeology and information on potential measurement biases. To maximise the acceptance and credibility, the Hydrographic Services were involved in three phases of the project through personal discussions. In addition to enhancing the acceptability, the information so obtained increases the accuracy of the flood estimates. A substantial part of the information was qualitative (soft) information based on the personal experience of staff members of the Hydrographic Services. Discussions also included past design values. A detailed documentation of the estimation process for each stream gauge produced was made available to the Hydrographic Services.

The overall design of the project is summarised in Fig. 2.

3 Data pre-processing

3.1 Flood data

The flood data used here consist of time series of observed maximum annual flood peaks for 698 catchments. The record length ranged from 5 to 182 years (Fig. 3) and the catchment size ranged from 1.6 to 131,488 km^2 with a median of 147 km^2. Most of the time series were part of a database hosted by the Hydrographic Services of Austria. Additional flood peak data were obtained from hydropower companies. In the first step of

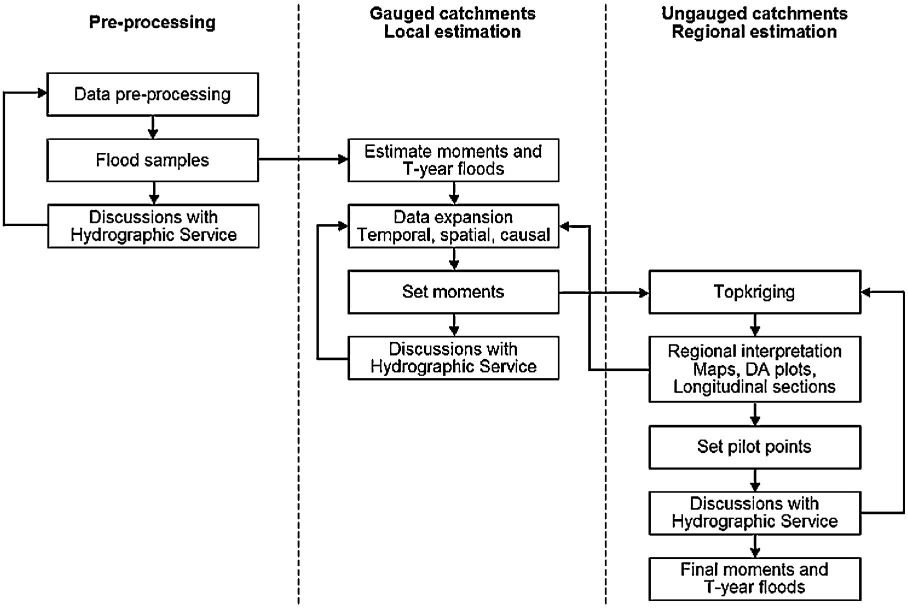

Fig. 2 Project design of estimating *T*-year flood discharges for 26,000 stream kilometres

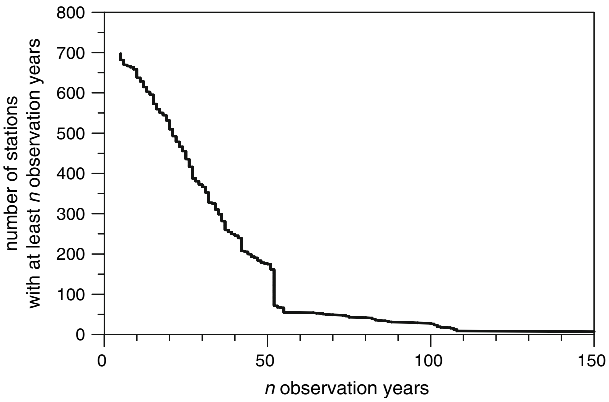

Fig. 3 Cumulative distribution of flood record length of the 698 stream gauges in Austria used here

pre-processing, the correct 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 errors were present the responsible staff member of the Hydrographic Services that had collected that data was interviewed. Some of the observed flood peaks were corrected as a result of the procedure or discarded from the data set. Outliers were analysed with particular care. Some of the highest observed flood peaks were caused by ice jams or wooden debris flow and information of the flood producing processes was used for the intrepretation of the probability of such outliers. Some gauges had been dislocated during their history, e.g. during the regulation of the stream. If the respective locations were close, the flood series were recombined to increase the record length. Some records were influenced by hydraulic structures such as reservoirs during part of the record length. Such stations were split into two records, representing pre-construction and post-construction conditions (Blöschl et al. 2000). An example of this is shown in Fig. 4. The time series of the station Malta at Sandriesen was split into records before and after 1977. Since 1977 the flood runoff at Sandriesen is highly influenced by the Kölnbrein reservoir and floods tend to be lower. For each station, the flood data quality was assessed and unreliable stations were

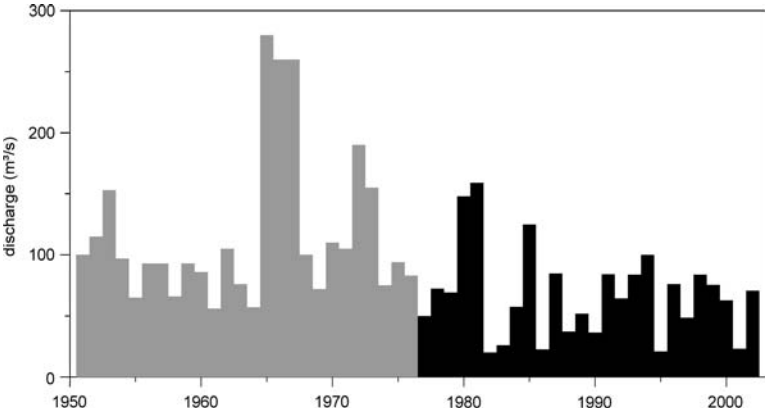

Fig. 4 Example of record (Malta at Sandriesen) that was split into two periods (1951–1976, 1977–2002) because of reservoir effects. Grey represents pre-construction and black represents the post-construction conditions

excluded from further analysis. The result of the screening was a consistent flood data set including an assessment of the data quality.

3.2 Other hydrologic data

A map of mean annual precipitation was derived using over 1,000 rainfall stations (Merz 2002) based on external drift kriging using terrain elevation as an auxiliary variable. Studies of regional flood types (Merz and Blöschl 2003a) and event runoff coefficients (Merz et al. 2006a) were available as additional information. Local studies of hydrological behaviour and photos are used if available.

Other available information with hydrological relevance are a 10 m digital elevation model (LFWRZ 2004), the Austrian 1:50,000 scale map (ÖK50), digital maps of hydrogeology (Schubert 2003), land use (Fürst and Hafner 2003), information on reservoirs and lakes (Fürst 2003) and soil types (ÖGB 2001). The different data sets used in the project are given in Table 1.

To account for the retention of reservoirs and lakes, the Flood Attenuation by Reservoirs and Lakes index *FARL* (IH 1999) was calculated for each catchment. It is a function of the areas of the lakes, the subcatchment area of each lake and total catchment area. In Fig. 5, the *FARL* index is indicated by the width of the streams. In Fig. 6, the location of flood retention reservoirs and hydro-power plants is shown. The size indicates the volume of the flood retention basin and the productivity of the hydro-power plants.

3.3 Catchment boundaries

At the core of the data preparation is the digital river network. Flood frequencies had to be estimated for each confluence, each river section, where streamflow measurements are available, for each inflow and outflow of lakes and reservoirs and at the headwaters of each stream in the digital river network. For each of the 7,775 specific locations, topographic catchment boundaries were available digitally.

Table 1 Data used in the project

Data type	Resolution	Source
Maximum annual flood peaks	698 catchments, 5–182 years	
Maximum annual daily precipitation	922 stations, 5–97 years	Merz et al. (1999)
Mean annual precipitation	1,066 stations, 31 years	Merz (2002)
Event runoff coefficients	49,918 events in 326 catchments	Merz et al. (2006a)
Flood types	11,518 maximum annual flood peaks in 490 catchments	Merz and Blöschl (2003a)
Digital elevation model	10 m resolution	LFWRZ (2004)
Austrian map (ÖK50)	1:50,000	
Hydrogeology	10 classes	Schubert (2003)
Land use data	11 classes (based on CORINNE)	Fürst and Hafner (2003)
Information of reservoirs and lakes	~9,000 lakes	Fürst (2003)
Soil types	10 classes (based on FAO)	ÖBG (2001)

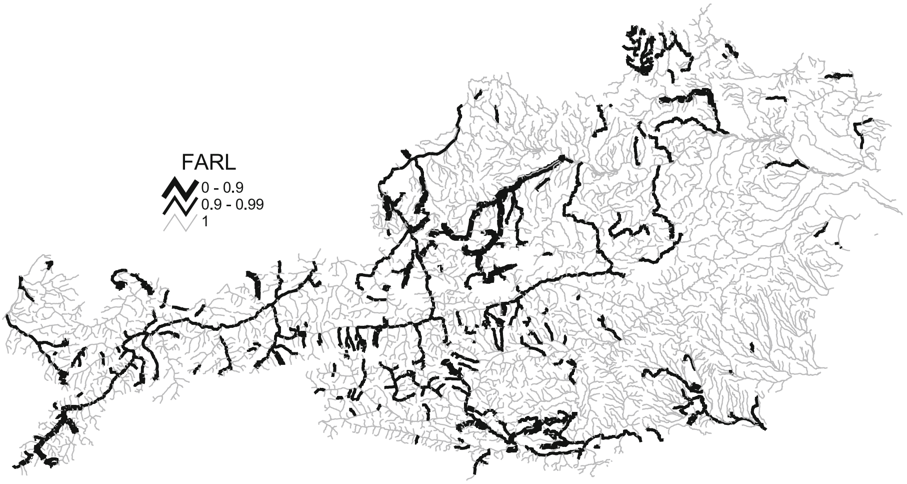

Fig. 5 Flood attenuation by reservoirs and lakes index *FARL*. Index of 1 denotes no effect, smaller indices indicate larger effects. Width of stream indicates *FARL* index

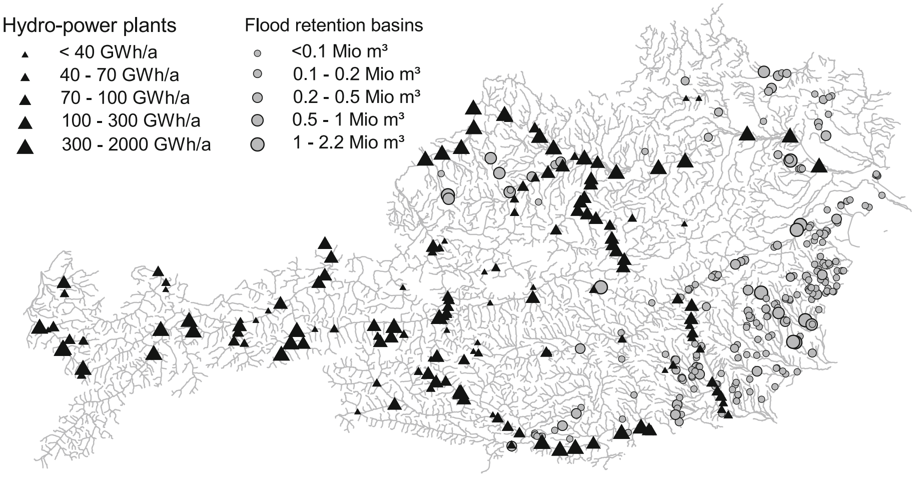

Fig. 6 Flood retention basins and hydro-power plants in Austria. Symbol size indicates volume and power production

For 2,811 river sections, notably headwater catchments and inflows and outflows of lakes, digital catchment boundaries were not available. To derive catchment boundaries, the digital catchment boundary of the next downstream catchment was overlaid with the 10 m digital elevation model and those boundary section with higher elevation than the river section of interest was separated. The endpoints of the section were then connected to the river section to close the catchment boundaries. A visual assessment revealed that the derived catchment boundaries most closely followed a manual derivation of catchment boundaries (Fig. 7). Some problematic boundaries were corrected manually. The catchment boundaries were checked for consistent topology. If no consistency in the up- and

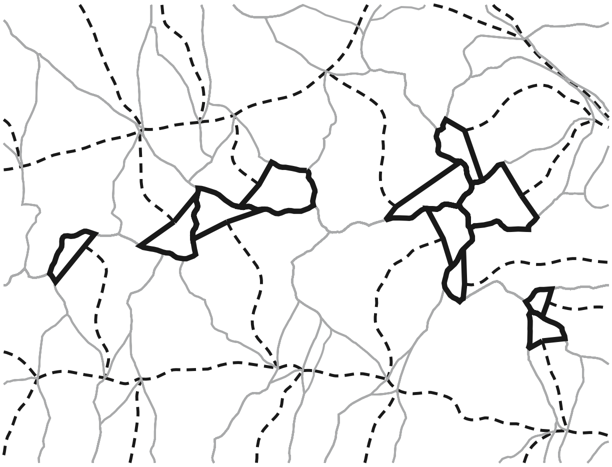

Fig. 7 Examples of derived headwater catchment boundaries. Dashed lines: river network, thin solid lines: digitised catchment boundaries, thick solid lines: derived headwater catchment boundaries

down-stream neighbours were found, correct topology were adjusted manually by following the streams downward.

4 Estimation of flood frequencies in gauged catchments

4.1 Estimation of parameters from flood samples

As a starting point, the pre-processed flood peak samples of all the 698 stream gauges were used to estimate the first three statistical moments: mean annual flood (*MAF*), coefficient of variation (C_V) and coefficient of skewness (C_S), which are a measure of the magnitude, slope and curvature of the flood frequency curve, respectively. These moments played an important role in the study, both for the expert assessment and as a basis for regional estimation. In parallel, the T-year floods were estimated from the moments. Previous analysis (Merz 2002; Merz and Blöschl 2005) indicated that the Generalised Extreme Value distribution (GEV) is flexible enough to accommodate the flood frequency situations encountered in Austria. The GEV distribution was hence adopted in the entire study to estimate the T-year floods from the moments. Confidence intervals were computed for different significance levels to comprise statistical uncertainty. Depending on the length of the observation period and the data quality, the moments, and thus the flood frequency curve, were adjusted manually. Usually the mean was estimated from the flood sample. Only in catchments with very short observation records or highly uncertain observations, was the mean adjusted. For each catchment C_V and C_S were adjusted manually based on the three types of expanded information. The relative importance of the statistical estimation and the assessment based on the expanded information was depended on the available data and detail of the information on local hydrological behaviour. For sites with long and reliable records, more weight was put on the estimation of C_V and C_S from flood data, while for sites with shorter observation records or unreliable data the estimation of C_V and C_S was mainly based on the expanded information.

4.2 Temporal information expansion

Here, two types of sources were used. The first were flood records of neighbouring catchments with longer observation periods to account for climate fluctuations. While there are formal climate adjustment methods available based on flood peak correlations (e.g. IH 1999, vol. 3, p. 212), the analysis of the study data indicated that much of the information is qualitative. For example, the timing of the flood indicated whether it was the same event in the two catchments compared. Also, comparisons by withholding part of the record suggested that for some catchments, flood measurements before the actual observation period would result in a shift of the mean annual flood, but for other catchments, particularly for those with one of few very extreme flood events in the actual observation period, climate variation mainly affect C_V and C_S. To capture the different effects, a manual adjustment was adopted in the project. The second source was historical flood events (e.g. Rohner et al. 2004). Flood marks, information on the exceedance or non-exceedance of a specific datum (bridges, streets, houses, etc.) as well as photographs of the inundation area were used, depending on availability. This information was used qualitatively to assess the magnitudes of the historical flood events relative to the largest floods on record. This information was mainly used to adjust the C_S as it controls the tail of the distribution. Conversely, the historic floods were used to assess the return period of the largest flood on record, in particular if this was an outlier. For example, if the recorded outlier was much larger than the historic floods (e.g. as assessed by the scale of the inundations as apparent in the photographs), a return period larger than the usual plotting position ($n + 1$ where n is the record length) was assigned. This information was also used to adjust the C_S.

4.3 Spatial information expansion

The flood data from neighbouring catchments were used to improve the at-site flood frequency estimation. For catchments up to a catchment area of about 10,000 km^2, maps with the 100 year flood colour coded and the moments indicated for each stream gauge were used in the assessment and hydrological reasoning. In the maps, the 100 year floods Q were normalised by

$$Q_N = Q \cdot A^{\beta} \cdot \alpha^{-\beta} \tag{1}$$

to a nominal catchment size of $\alpha = 100$ km^2, as the focus was on the spatial variability of runoff generation. These maps were assisted by discharge-area (DA) plots for 28 regions in Austria to examine the change of discharge with catchment area. In the DA plots three estimates of the 100 year flood were indicated, 100 year flood directly estimated from the local samples, regionalised 100 year floods based on local flood data and data from neighbouring stations, and regionalised 100 year floods, without using local flood data (i.e. Jack-Knifing estimates). Regionalised flood estimates were determined using the Top-kriging approach as presented in Sect. 5.1 of this article. Additionally, hydrological similarity between the stream gauge of interest and the neighbouring stations were assessed by expert judgement by a range of sources of information including typical storm track patterns. In setting the flood moments, the reliability of the local flood data were taken into account vis-a-vis the regional information. In the case of large rivers, (i.e. with catchment area larger than 10,000 km^2), where routing effects are very important the T-year flood runoff was plotted against stream length as longitudinal profiles. The variability of the flood runoff along the river was adjusted based on an assessment of inundation effects. On the Danube, for example, there exist very long records of up to 150 years, so the *T*-year floods can be estimated more reliably than in smaller catchments. However, the accuracy required is higher, so the spatial information expansion from upstream and downstream gauges is also important as some of the gauges only have 30 years of record. In the 85 km reach of the Danube upstream of Vienna, the 100 year flood decreases from 11,100 to 10,400 m^3/s, even though the catchment area increases from 96,000 to 102,000 km^2. This is because of inundation into the Tullner Feld flood plain.

4.4 Causal information expansion

To obtain a first understanding of the flood generation processes, the five types of causative flood mechanisms of Merz and Blöschl (2003a) were used. The types were long-rain floods, short-rain floods, flash floods, rain-on-snow floods, and snowmelt floods. Catchments dominated by flash-floods due to short, high intensity rainfalls, mainly of convective origin, usually exhibit low MAF, large C_V and large C_S, while catchments dominated by long-rain floods, i.e. synoptic or frontal type storms, the MAF tend to be larger, and C_V and C_S smaller. The presence of soil moisture points to small C_V and C_S (Merz and Blöschl 2003b). For a more detailed analysis, the rainfall records in the catchment of interest were analysed. In principle, one can derive the flood frequency curve from the rainfall frequency curve (e.g. Sivapalan et al. 2005) but in a regional study there is rarely sufficient information to do this in a rigorous way. A simplified method was therefore used here that uses rainfall frequency information. Specifically, the gradex method (Guillot 1972) was used that is based on the assumption that the average maximum storage capacity of the catchment is reached at a threshold return period and any additional rainfall becomes runoff without losses. Although statistically not rigorous, the method was shown to give robust results in Austria with a tendency of overestimating flood peaks for catchments with low specific discharges (Merz et al. 1999). As the gradex method estimates the tail of the distribution it was used in this study to adjust the C_V. Annual series of maximum daily rainfall data were used as an input as long records (typically 100 years) are available in Austria. This means that the application of the method was limited to those catchments with response times of not much less than a day as it is for these where daily rainfall maxima are relevant. Information on the response times of Austrian catchments is given in Merz and Blöschl (2003a). An example of the application of the method is shown in Fig. 8. The method assumes that the tail of the flood distribution is parallel to the transformed rainfall distribution beyond a threshold return period (chosen as $T = 20$ years in this case). As for the observed flood peaks only a small portion of rainfall becomes runoff while the gradex method assumes that all of the additional rainfall becomes runoff, the gradex slope is steeper than that of the flood frequency curve fitted to the data. In this particular catchment, this extrapolation behaviour is very realistic as the maximum flood (not included in the flood sample for illustration purposes) was 141 m^3/s and occurred in August 2005. For catchments where the response time is much shorter than a day the gradex method cannot be used. Instead, event runoff coefficients (i.e. the portion of rainfall that becomes direct runoff during an event) were used that were estimated by Merz et al. (2006a). For catchments with large runoff coefficients the flood frequency curve would not be expected to increase in slope as the return period increases but for catchments with small runoff coefficients one would expect that the runoff coefficients will increase, so the tail may be steeper than the observed flood peak data would suggest. The C_S was hence

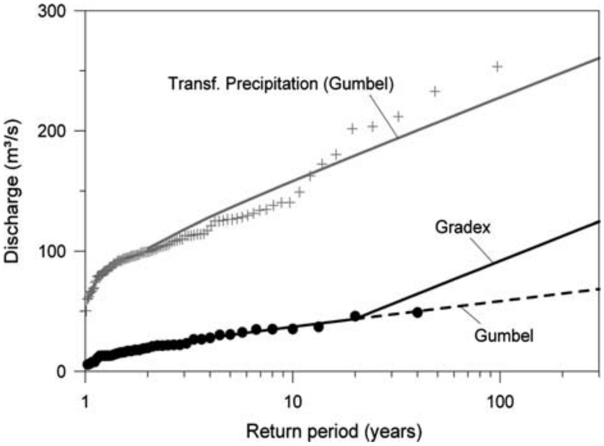

Fig. 8 Gradex method for the Trisanna at Galtür (97 km^2 catchment area). Transformed precipitation data of the station Partenen is shown as plusses

increased in these cases. Other pieces of information used in the causal information expansion step was the shape of the hydrograph with dampened hydrographs indicating a large proportion of subsurface runoff during an event.

4.5 Discussion with Hydrographic Services and final estimates

Based on the above information, the statistical moments for each stream gauge were set manually. For about half the stream gauges the moments were similar to those estimated directly from the flood samples, particularly for long records with high quality data. For the other stream gauges, the moments were different. In a significant number of instances the C_S was larger than that of the flood sample, as indicated by the data expansion. In some instances the C_V was larger as well. There were also a number of gauges were C_S was set smaller than that indicated by the flood sample, in particular when outliers were present and their return period was estimated from the expanded information. Examples are shown in Fig. 9. The Vandans station (Fig. 9a) has a record of 52 years with high quality data. Runoff coefficients are large and the gradex tail is of similar slope as the flood frequency curve, and the stream gauges in the regions are similar so there was no indication of increasing the steepness of the curve. The moments were hence set to those from the flood sample. In contrast, the record of St. Jakob (Fig. 9b) is shorter and there was indication that the measurements may not be fully reliable. Runoff coefficients were medium, so the curvature (i.e. C_S) was not increased beyond that of the sample but the slope (i.e. C_V) was increased as indicated by similar catchments in the region. The results from these analyses were discussed with staff members of the Hydrographic Services, including the hydrological reasoning, and compared with their personal experience. In a number of instances very useful information was provided by the staff members. In particular, information about local weather patterns and local hydrogeology not apparent in the data set used. In these cases, the moments were adjusted to those suggested by the staff members of the Hydrographic Services. In other instances, no additional information was provided but the magnitude of uncertainty was assessed differently. As one of the objectives of the study was to estimate the T-year flood by a consistent procedure across the country and the staff members in the nine offices of the Hydrographic Services may have different understanding of uncertainty, in these cases the suggestions of the Hydrographic Services were

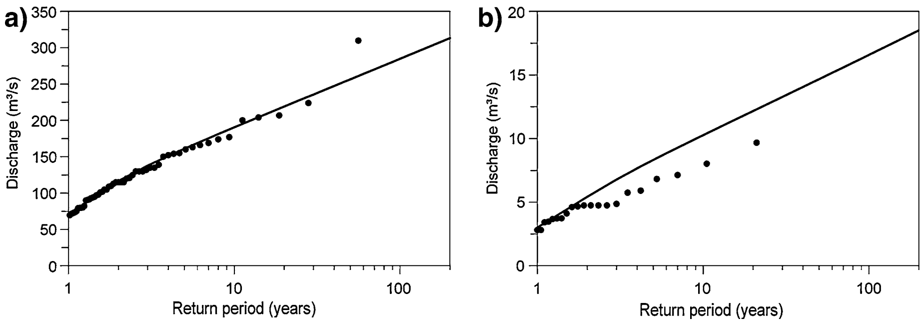

Fig. 9 Examples of flood frequency curves. (**a**) Vandans (511 km^2) with reliable local flood data, (**b**) St. Jakob (56 km^2) with unreliable data where the flood frequency curve was adjusted to the expanded information

not adopted. The results of this step of the study are shown in terms of the moments (mean annual flood, *MAF*, coefficient of variation, *CV*, and coefficient of skewness, *CS*) of the 698 stream gauges in Austria manually set (Fig. 10). *T*-year flood discharges are calculated from the moments using the GEV distribution.

5 Ungauged catchments

5.1 Regionalisation by Top-kriging

For the 7,077 ungauged catchments the flood moments are estimated automatically by a regionalisation method from the flood data in a region, and pilot points are set to adjust the regional patterns manually based on auxiliary information. In Merz and Blöschl (2005) the predictive performance of various types of automatic regionalisation methods were examined based on a Jack-knifing comparison for 575 Austrian catchments indicating that geostatistical methods outperformed other methods such as regressions and the Region of Influence approach. A geostatistical regionalisation method known as Top-kriging was hence chosen to regionalise the flood moments. Top-kriging takes both catchment area and distance along the stream network into account (Skøien et al. 2006) and is the most natural way of statistically interpolating along stream networks as no additional assumptions beyond the standard geostatistical assumptions are needed. Also, in Top-kriging it is straightforward to take into account the length of the flood records by the KUD (kriging of uncertain data) approach (Merz and Blöschl 2005). In the KUD approach, the local uncertainty or error variance of the moments is estimated as a function of record length. Stations with short records can hence be used in the regionalisation but get smaller weights than stations with long records. A number of additional controls were considered by adjusting the mean annual flood *MAF*:

$$MAF^* = \ln(MAF \cdot A^{\beta} \cdot \alpha^{-\beta} \cdot FARL^{-\gamma} \cdot F_P) \qquad (2)$$

Specific flood discharges tend to decrease with catchment area and this effect was accounted for by scaling *MAF* by catchment area *A* where α is the reference catchment area of 100 km^2 and β ranged between 0.25 and 0.40 depending on the flood process types. For dry regions in Austria where flash floods prevail, β was set to 0.4 reflecting the presence of

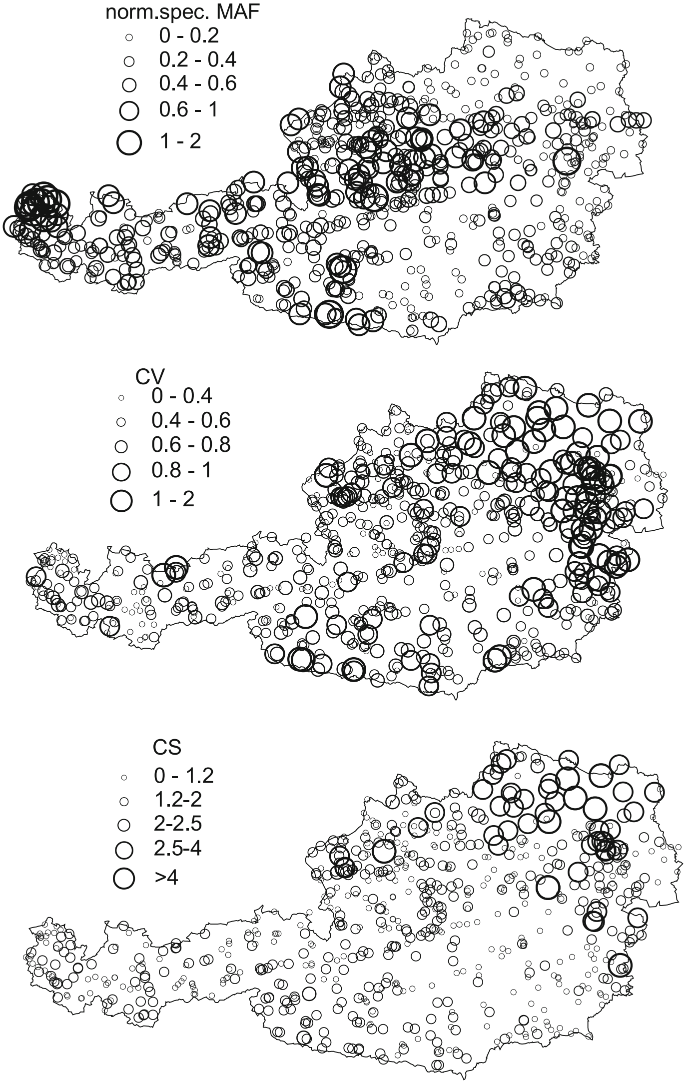

Fig. 10 Flood moments (mean annual flood, *MAF* ($m^3/s/km^2$), coefficient of variation, C_V (−), and coefficient of skewness, C_S (−), for 698 stream gauges in Austria as a result of the estimation procedure

high intensity storms in small catchments while in the wet regions on the northern fringe of the Alps where long rain (synoptic) events prevails β was set to 0.25 reflecting the large scale of frontal systems. In the rest of Austria, β was set to 0.33 which correspond to the average trend in Austria. To account for the retention of reservoirs and lakes, the Flood Attenuation by Reservoirs and Lakes index *FARL* (IH 1999) was calculated for each catchment and again used to scale *MAF*. Based on analyses of Austrian lake inflow and outflow data γ was found as 1.5. In Austria, the floods are closely related to mean annual rainfall as index of soil moisture state and river morphology (Merz et al. 2006b). To account for this effect, *MAF* within regions were correlated against mean annual catchment rainfall and the residual between the regression line and the local value was expressed as a factor F_p which was used to scale *MAF*. In most instances, F_p and *MAF* were positively correlated. As the distribution of *MAF* was skewed all *MAF* values were logarithmically transformed before regionalisation. The three flood moments (MAF^*, C_V, C_S) were then regionalised to ungauged catchments by Top-kriging. For each ungauged catchment, Eq. 2 was inverted to estimate *MAF* from the Top-kriging estimates of MAF^*. For small catchments, the area scaling increased the specific discharges, for catchments with lakes the lake scaling decreased the specific discharges and for high rainfall areas, the precipitation scaling increased the specific discharges. As a final step of the automatic method, the *T*-year floods were estimated from the flood moments using the Generalised Extreme Value (GEV) distribution for all nodes of the stream network. As an example, the normalised specific 100 year flood (Eq. 2) for the Danube (Donau) region in Upper Austria is shown in Fig. 11. There is a high variability in the specific flood discharges of the tributaries. The tributaries from the North (e.g. Naarn, Klambach, Sarmingbach) show much lower specific discharges, while the tributaries from the south exhibit higher specific discharges than the Danube river. The Top-kriging estimates on the Danube river are similar to the measurements on the Danube river and do not change much along the reach. In the Top-kriging procedure the estimates on the main rivers are not much affected by the measurement of small tributaries as Top-kriging takes catchment area and the nested structure of the river network into account. However, estimates using other distance based methods such as Ordinary kriging differs substantially as they are too much influenced by the measurements at small tributaries along the main river.

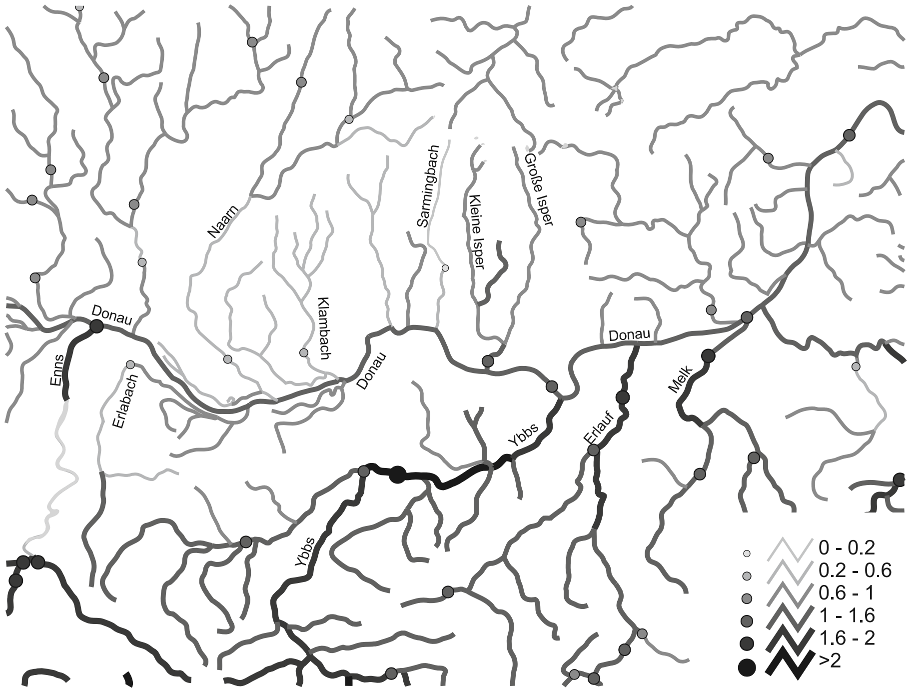

Fig. 11 Estimates of the normalised specific 100 year flood from Top-kriging (shown as width of the stream network) in the Danube (Donau) region in Upper Austria. The estimates of the gauged catchments are shown as circles. Units are in $m^3\ s^{-1}\ km^{-2}$

5.2 Regional interpretation

To account for local particularities of catchments, an iterative regionalisation approach was adopted. The estimates of the automatic regionalisation approach were used as a starting point for the manual adjustment which was based on hydrological reasoning and additional information in a similar way as in the gauged catchment case. For large rivers, *T*-year flood runoff was plotted against stream length as longitudinal profiles. For small- to medium-sized catchments, maps with the 100 year flood colour coded and the moments indicated for each node were overlaid with other information, such as hydrogeology (in particular presence or absence of quaterny sedimentary valley fillings), soil types, land-use data and the Austrian map at the 1:500,000 scale (in particular the degree of incision of stream channels), information on hydraulic structures and water transfers, and information on technical flood reports as available. In a first step, each gauge was assessed whether it represented regional flood behaviour or whether it represented local flood behaviour based on the above information. Typically, gauges downstream of reservoirs were locally representative, as were catchments with local gravel fillings of the valleys that were not present in neighbouring valleys. Local versus regional representativeness was coded as an index assigned to each stream gauge. In a second step, each ungauged river reach was examined manually based on the above information. If local behaviour was deemed not to be captured by the automatic regionalisation approach, pilot points were added to individual nodes to adjust the regional patterns of the moments. These pilot points were used in the Top-kriging procedure in a similar way to the moments estimated from the flood samples, either as regionally representative pilot points or as locally representative pilot points. An example of the use of pilot points is shown in Fig. 12. The flood runoff at the river Malta (Fig. 12) is highly influenced by a hydro-power plant and the gauges at the upper Malta river are not representative for the region. Therefore, all gauges are set to local pilot points, while at the neighbouring river Lieser the gauging station is used as a regional

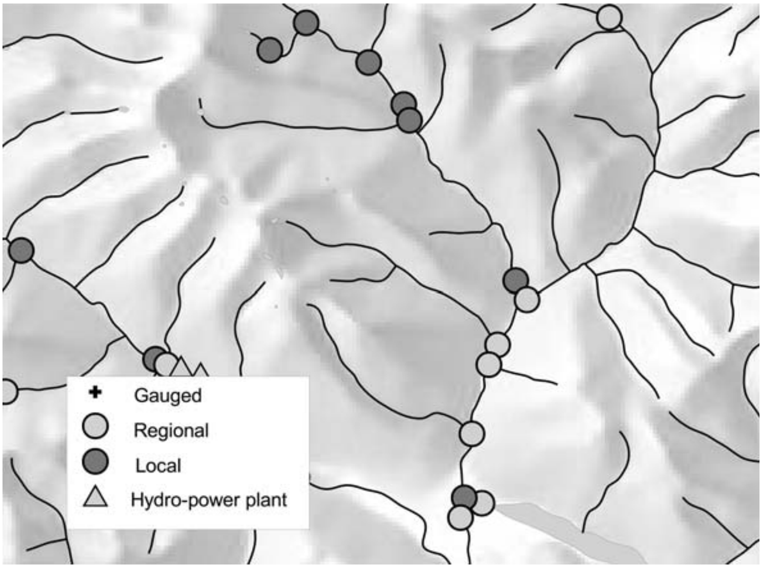

Fig. 12 Pilot points, local points, regional points to account for local versus regional representativeness

pilot point. The influence of the hydropower plant can be neglected after the confluence of Malta and Lieser, due to the large contributing area of the Lieser. The downstream gauging stations are hence used as regional pilot points.

An important case of local particularities not covered by automatic regionalisation schemes in Austria are hydraulic structures such as retention basins (Fig. 6). As the exact hydraulic characteristics were not available for most of the structures, the flood moments were adjusted manually based on the volume information available.

In an iterative way, the moments at the stream gauges and pilots points and the local/regional representativity index were used to recalculate the flood moments for all nodes using Top-kriging. The iterative concept allowed an efficient combination of the automatic regionalisation procedure with manual expert judgement.

5.3 Discussion with Hydrographic Services and final estimates

The results from these analyses were, again, discussed with staff members of the Hydrographic Services, including the hydrological reasoning, and compared with their personal experience. The estimates were adjusted in a similar way as in the gauged catchment case. The results of this step are the final results of the study. Figure 13 shows the 100 year flood for the entire stream network of 26,000 km in Austria. The 100 year flood discharges are, of course, mainly related to catchment size although pronounced regional patterns exist. The highest specific flood discharges occur at the northern fringe of the Alps. Topographic enhancement effects often result in high and persistent rainfalls. Due to the high pre-event soil moisture and high rainfall rates, large runoff rates occur regularly. In addition, the soils and the Flysch geology contribute to large discharges. At the southern fringe of the Alps some of the largest floods in these catchments have resulted from high intensity precipitation associated with the advection of moist air from the Mediterranean. In the inner part of the high Alps specific discharges are much lower as catchments are much more orographically sheltered. The smallest specific flood discharges

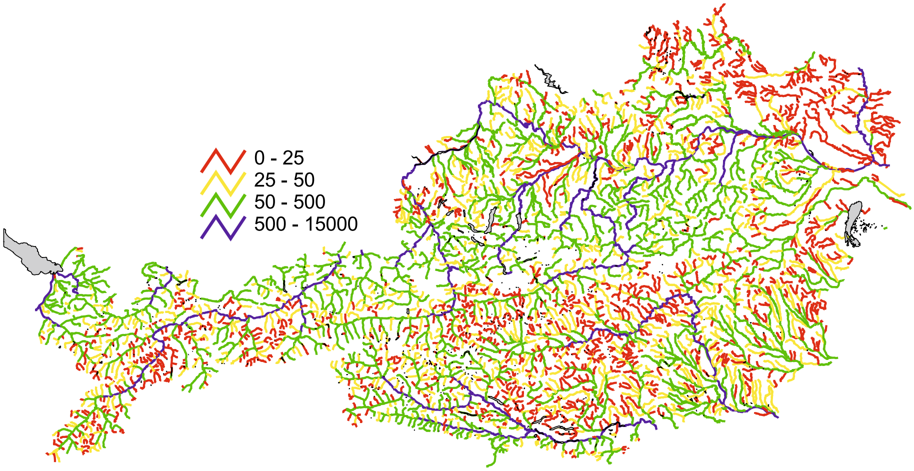

Fig. 13 Hundred year flood (m^3/s) for 26,000 km of streams in Austria as a result of the estimation procedure

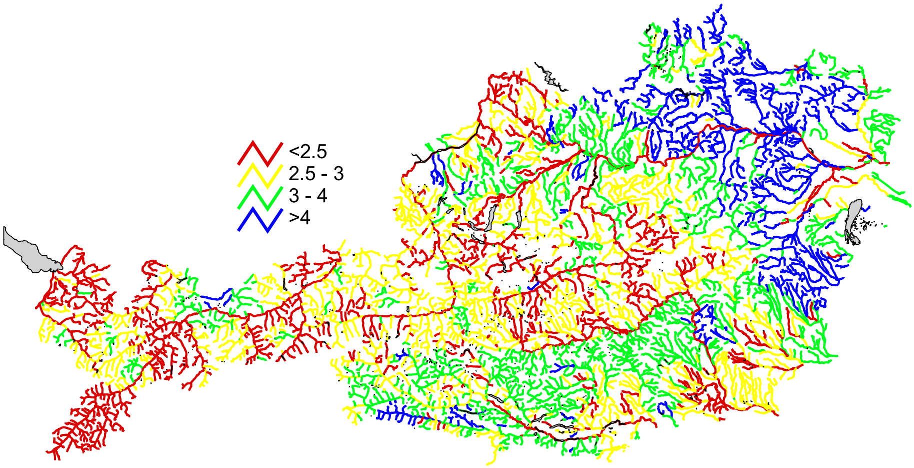

Fig. 14 Ratio of the 100 year flood and the mean annual flood which is an index of the steepness of the flood frequency curve

occur in the lowlands of eastern Austria. The small values are related both to much smaller rainfall inputs than in other parts of Austria and to relatively dry catchment conditions towards the Slovak and Hungarian border. Distinct regional patterns can also be found in the shape of the flood frequency curve, illustrated in Fig. 14 as the ratio of 100 year flood to mean annual flood discharges. This ratio is an indicator of the steepness of the flood frequency curve. In the wet catchments at the northern fringe of the Alps, the 100 year flood discharges are only 2–2.5 times higher than mean annual floods. In the dry catchments in eastern Austria the ratio is much larger (more than 5) which is a result of the increase of runoff coefficients with increasing return period of the flood. Mean annual floods tend to be small, but much higher floods can occur, very rarely. An example of such extreme floods is the flood event in August 2002 in northern Austria, which was four times as large as the largest flood on record (Gutknecht et al. 2002).

6 Discussion and conclusions

The HORA project was the first nation wide estimation of flood frequencies in Austria. The scale of the project—26,000 km of streams—required a strategy that had the capability of estimating the *T*-year flood for a large number of catchments (more than 10,000) within the given resources, and at the same time provide a level of accuracy that was acceptable to the local water authorities. This goal was addressed by a combination of automatic methods and manual assessments by hydrologists. Experience from this study indicated that this strategy is indeed feasible. The combined approach in the project proved to be very efficient. With the manual adjustment of automatically estimated flood moments it was possible to estimate *T*-year floods for all catchments within 12 months.

Traditionally, estimation of the *T*-year flood in a regional context has been based on flood peak samples only. The expanded information used in this study was extremely useful for enhancing the robustness and reliability of the estimates. The temporal, spatial and causal information expansion consisted of combining various sources of hydrological information as available. For about half of the stream gauges the use of expanded information resulted in a significant change of the initial statistical estimates of the *T*-year floods. Overall, the estimates of the *T*-year floods for the stream gauges of this study were deemed more reliable than statistical estimates from the flood samples alone, based on the judgement of the staff of the Hydrographic Services. While the accuracy was not always at a level required for detailed design studies at the local scale (as usually obtained by rainfall runoff modelling) it was within a range perfectly acceptable for flood hazard zoning. This was corroborated by leave-one-out cross validation tests. The expanded information was particularly useful for assessing the return period of outliers. For the case of ungauged catchments, various sources of information were combined in a similar way. Although it is more difficult to assess the accuracy of the estimates for ungauged catchments, there was certainly a high level of credibility attached to the estimates as all available information could be incorporated in an informal way, such as information on the local hydrogeologic characteristics and hydraulic structures. With the combined approach it was possible to couple a nation wide consistent approach, based on uniform assumptions and information, with a large amount of information on the local hydrology.

An important step in estimating the flood discharges was the involvement of the Hydrographic Services. The understanding of their staff members of the local hydrologic conditions turned out to be extremely helpful in estimating the flood discharges. Similarly, important was their assessment of the reliability of the flood peak data. Additionally, the involvement of the Hydrographic Services clearly increased the acceptance of the results of this study both by the staff of the Hydrographic Services themselves as the responsible water authority and by the end-users of the flood hazard maps.

The focus of this study has been on estimating discharges as a basis of flood hazard mapping. Given that the *T*-year floods have been estimated on a national scale in a consistent way it can be expected that the results will influence future flood estimates of water authorities and other entities for other purposes such as design. In the past, a wide range of methods has been used for flood estimation, depending on available data and tools, and these have often involved a high degree of personal judgement (Moser 2006). Design discharges usually include some extra safety while the *T*-year flood discharges of this study have been intended to represent the expected discharges with over- and underestimation being equally likely. The process of understanding how differently defined *T*-year flood values for the same river reach can co-exist in an institutional framework—and in fact benefit from each other—is currently under way.

The flood discharges estimated in this study have been transformed by other project partners to flood hazard zones using hydraulic modelling. The flood hazard zones have been integrated into an Internet application (http://www.hochwasserrisiko.at) with public access. For georeferencing, the Internet application shows maps or areal photographs, depending on scale, along with the flood hazard zones. These are shown in three hazard categories associated with 30 year, 100 year and 200 year flood return periods.

Acknowledgements The HORA project was funded by Austrian Ministry of Agriculture, Forestry, Environment and Water Management and the Austrian Association of Insurance Companies. The authors would like to thank the Austrian Academy of Sciences (APART [Austrian Programme for Advanced Research and Technology]—fellowship) for financial support in methods development and the Austrian Hydrographic Services for providing the hydrographic data and for their collaboration in the HORA Project. We would like to particularly thank the staff from the Humer consulting office for the good collaboration and fruitful discussions in the project.

References

Blöschl G, Piock-Ellena U, Merz R (2000) Abflußtypen-Klassifizierung als Basis für die Regionalisierung von Hochwässern. Endbericht 2000, Österreichische Akademie der Wissenschaften (HÖ-12). Institut für Hydraulik, TU-Wien

Bobée B, Rasmussen PF (1995) Recent advances in flood frequency analysis. U.S. National Report to International Union of Geodesy and Geophysics 1991–1994. Rev Geophys 33(supp.):1111–1116

Bradbrook K, Waller S, Morris D (2005) National floodplain mapping: datasets and methods—160,000 km in 12 months. Nat Hazards 36:103–123

DVWK (Deutscher Verband für Wasserwirtschaft und Kulturbau) (1999) Statistische Analyse von Hochwasserabflüssen. Wirtschafts- und Verl.-Ges. Gas und Wasser, Bonn (DVWK-Merkblätter zur Wasserwirtschaft; H 251)

EU (Commission of the European Communities) (2006) Proposal for a Directive of the European Parliament and of the Council on the assessment and management of floods {SEC(2006) 66}, Brussels, 18.01.2006, COM(2006) 15 final, 2006/0005(COD), http://www.ec.europa.eu/environment/water/flood_risk/key_docs.htm

Fürst J (2003) Fliessgewässer und Seen. Karte 1.2, Hydrologischer Atlas Österreich. Österreichischer Kunst und Kulturverlag und Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Wien

Fürst J, Hafner N (2003) Bodenbedeckung. Karte 1.5, Hydrologischer Atlas Österreich. Österreichischer Kunst und Kulturverlag und Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Wien

Guillot P (1972) Application of the method of gradex. In: Schulz EF, Koelzer VA, Mahmood K (eds) Floods and droughts. Proceedings of the Second International Symposium in Hydrology, Fort Collins, Colorado, USA, Water Resources Publications, pp 44–49

Gutknecht D, Resler Ch, Blöschl G (2002) Das Katastrophenhochwasser vom 7. August 2002 am Kamp – eine erste Einschätzung. Elektrotechnik und Informationstechnik 119(12):411–413

Hall JW, Sayers PB, Dawson RJ (2005) National-scale assessment of current and future flood risk in England and Wales. Nat Hazards 36:147–164

IH (Institute of Hydrology) (1999) Flood estimation handbook. Institute of Hydrology, Wallingford, UK

Kron W, Willems W (2002) Flood risk zoning and loss accumulation analysis for Germany. Proceedings of an International Conference on Flood Estimation, Berne, März 6–8, 2002, International Commission for the Hydrology of the Rhine basin, CHR Report II-17, Swiss Federal Office for Water and Geology, S. 549–558. Land-, Forst-. und Wasserwirtschaftliches Rechenzentrum (LFWRZ) (2004), personal communication

Mandelbrot BB, Wallis JR (1968) Noah, Joseph, and operational hydrology. Water Resour Res 4(5):909–918

Merz R (2002) Understanding and estimating flood probabilities at the regional scale. Dissertation. Wiener Mitteilungen, Wasser-Abwasser-Gewässer, 132, Institut für Hydraulik, TU Wien, 346 pp

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

Merz R, Blöschl G (2003b) Normierte mittlere Hochwasserspende (standardized mean specific flood discharge). Karte 5.4, Hydrologischer Atlas Österreich. Österreichischer Kunst und Kulturverlag und Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Wien

Merz R, Blöschl G (2005) Flood frequency regionalisation—spatial proximity vs catchment attributes. J Hydrol 302(1–4):283–306

Merz R, Blöschl G, Piock-Ellena U (1999) Zur Anwendbarkeit des Gradex-Verfahrens in Österreich. Österr Wasser- und Abfallwirtschaft 51:291–305

Merz R, Blöschl G, Parajka J (2006a) Spatio-temporal variability of event runoff coefficients. J Hydrol 331: 591–604, doi:10.1016/j.jhydrol.2006.06.008

Merz R, Blöschl G, Humer G, Hofer M, Hochhold A, Wührer W (2006b) Hochwasserrisikoflöchen Österreich (HORA) – Hydrologische Arbeiten; Technical report to the Federal Ministry of Agriculture, Forestry, Environment and Water Management. Institute for Hydraulic and Water Resources Engineering, Vienna University of Technology

Moser J (2006) Regionalisierung von hydrologischen Kennwerten in Kärnten, in: Wiener Mitteilungen, Wasser-Abwasser-Gewässer, Band 197. Methoden der hydrologischen Regionalisierung, Institut für Wasserbau und Ingenieurhydrologie, TU Wien, S. 109–130

ÖBG (2001) Bodenaufnahmesysteme in Österreich. Mitteilungen der Österreichischen Bodenkundlichen Gesellschaft 62, Wien

Rodda HJE (2005) The development and application of a flood risk model for the Czech Republic. Nat Hazards 36:207–220

Rohner K, Berger I, Steiger H, Moser J, Pichler F, Sereinig N (2004) Hochwasserchronik Kärnten 792–2003, Amt der Kärntner Landesregierung, Abteilung 18 Wasserwirtschaft, Klagenfurt

Schubert G (2003) Hydrogeologie. Karte 6.2, Hydrologischer Atlas Österreich. Österreichischer Kunst und Kulturverlag und Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Wien

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:W0612, doi:10.1029/2004WR003439

Skøien J, Merz R, Blöschl G (2006) Top-kriging—geostatistics on stream networks. Hydrol Earth Syst Sci 10:277–287