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ESTIMATING FLOOD RISK IN AUSTRIA

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ABSTRACT

This paper summarises the methods of estimating 30, 100 and 200-year floods for 26,000 km of Austrian streams. The estimates are based on maximum annual flood peak data measured at 698 stream gauges in Austria; runoff coefficients for a large number of events; precipitation data from 1066 stations; hydrogeologic, soil and land use data; and information on reservoirs and lakes. For gauged catchments, the floods are estimated by combining various sources of information that represent causal processes, and regional information, as well as historical information if available. For ungauged catchments, an initial estimate was provided by a geostatistical method, which was refined by the expert judgment of the hydrologists involved in the project. An application of the flood estimates to flood zone mapping in the context of the recent Flood Directive of the European Union is discussed.

KEY WORDS

- flood estimation
- regionalisation
- flood frequency
- ungauged catchments

1. INTRODUCTION

Flood estimation is a major issue in Austria. Flood estimates of a given return period (or probability of exceedance) are needed for a range of purposes in Civil Engineering, including design of dam spillways, estimating levee crests, design of river training works, culvert design, and risk zoning. The latter application has become particularly relevant after the major flood events in 2002 and 2005 in Europe. Also, the recently adopted European Flood Directive (EU, 2007) recently adopted states in Article 6: "1. Member States shall, at the level of the river basin district, or unit of management ... prepare flood hazard maps and flood risk maps, at the most appropriate scale ..." and further "3. Flood hazard maps shall cover the geographical areas which could be flooded according to the

following scenarios: (a) floods with a low probability, or extreme event scenarios; (b) floods with a medium probability (likely return period ≥ 100 years); (c) floods with a high probability, where appropriate." An additional interest in Austria resides with the Austrian Association of Insurance Companies in terms of assessing the flood risk of insured properties.

The paper summarises the method of estimating the flood probabilities for Austria. The method was applied to estimate the flood discharges associated with three return periods, i.e., low probability or 200-year return period; medium probability or 100-year return period; and high probability or 30-year return period. The estimates were obtained for a total of 26,000 km of streams in Austria which, for the discretisation used, is equivalent to 10,000 river cross sections. The research was part of a national flood mapping project known

as HORA (HochwasserRisikioflächen Austria – Flood Risk Zones in Austria). The methodology was developed to account for the specifics of the task in Austria. Three guiding principles were adopted: (a) A combination of automatic methods and expert judgments by hydrologists. The expert judgment component was deemed essential to be able to account for information that cannot be quantified easily such as the role of geological fractures and the effect of retention basins on flood runoff; (b) A combination of various sources of information. Here, the main focus was on expanding the information beyond that of the flood peak sample at hand in order to obtain more reliable flood estimates than is possible with local statistical estimation methods alone. Specifically, the information was expanded in three ways: Temporal information expansion extends the flood records further into history. Spatial information expansion uses flood information about neighbouring catchments. Causal information expansion explores the flood generation processes. These pieces of information include both quantitative and qualitative (soft) information. The underlying philosophy of using hydrological reasoning in flood estimation is detailed in Merz and Blöschl (2008ab); and (c) Involvement of Hydrographic Services. It was deemed very important to closely collaborate with the local hydrographic services and the river authorities that are familiar both with data quality and with the local catchment characteristics in order to strengthen the data base

and reliability of the estimates. An additional benefit of involving the hydrographic services was to increase the acceptability of the estimates obtained as these are the authorities responsible at the state level for issuing the design values of the floods of a given return period.

2. DATA SCREENING

In this study the series of maximum annual flood peaks of 698 catchments, with catchment areas ranging from 1 to 131,488 km² are used. The length of the flood records varies between 5 and 182 years. Most of the time series are part of a data base hosted by the Hydrographic Service of Austria. Additional flood peak data were obtained from hydropower companies. In a first pre-processing step the location of each gauging station was checked manually. Although the Austrian streamflow data are of excellent quality, each flood record was screened manually by visual comparison to neighbouring stations. If in doubt as to whether the record contained errors, the responsible staff member of the Hydrographic Services that had collected the data was interviewed. Some of the observed flood peaks were corrected as a result of the procedure or discarded from the data set (Merz et al., 2007). Some records were influenced by the construction of hydraulic structures such as reservoirs over

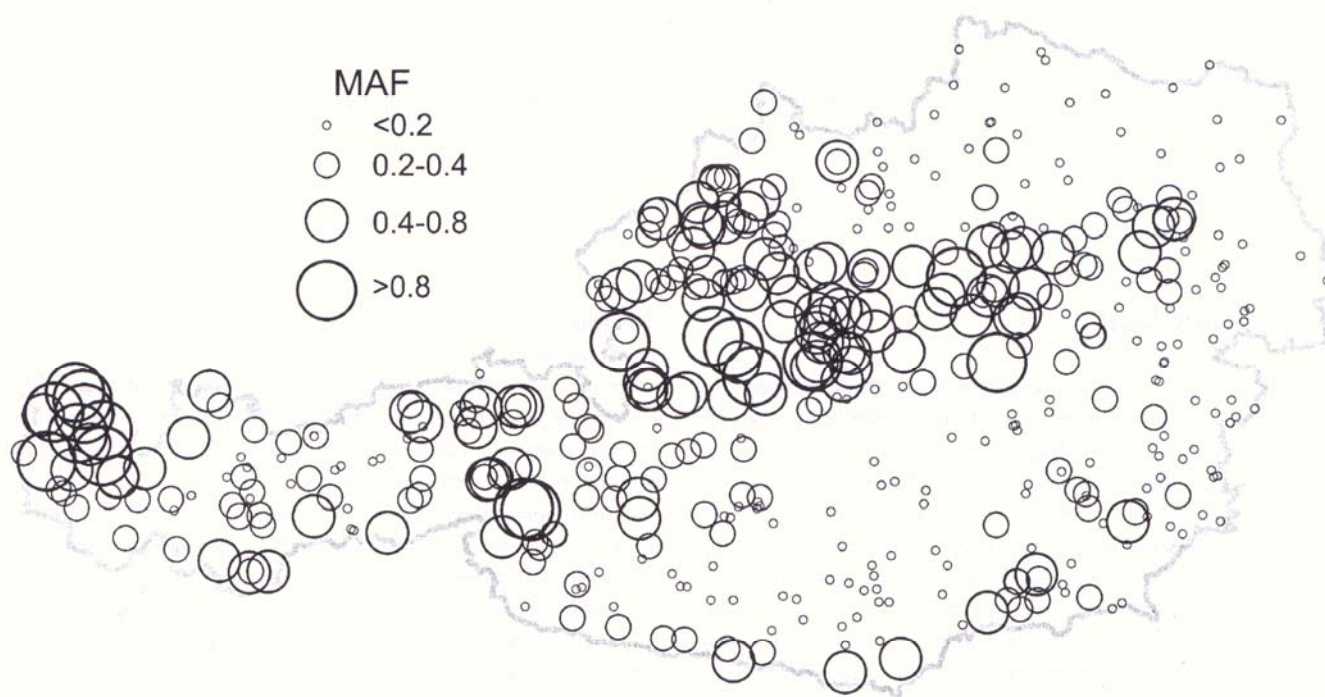


Fig. 1 Mean annual floods MAF (m³/s/km²) for 698 stream gauges in Austria.

the course of the record. Such stations were split into two records, representing pre-construction and post-construction conditions. As an example, Fig. 1 shows a map of the mean annual flood *MAF* (i.e., the mean of the annual flood peak series) for each of the 698 stream gauges. The *MAF* tends to be high in catchments at the northern rim of the high Alps. In that area, the *MAF* is higher than $0.4 \text{ m}^3/\text{s}/\text{km}^2$ and in some catchments larger than $0.8 \text{ m}^3/\text{s}/\text{km}^2$. In the higher alpine catchments *MAF* tends to be somewhat smaller, with values usually between 0.2 and $0.4 \text{ m}^3/\text{s}/\text{km}^2$. In the lowlands of eastern Austria the smallest *MAF* are observed, with values usually lower than $0.2 \text{ m}^3/\text{s}/\text{km}^2$.

A number of hydrologically relevant catchment attributes were used. In order to characterise the behaviour of runoff generation on the event scale, the results of a regional analysis of rainfall-runoff events in Austria are used (Merz et al., 2006), where event characteristics such as event runoff coefficients and event rainfall depth have been back-calculated from hourly runoff data, hourly precipitation data and snowmelt estimates. A total of about 120,000 events were analysed over the period 1981 to 2000. A detailed description of the methodology is given in Merz et al. (2006). Long-term mean annual precipitation (MAP) and information on daily precipitation were derived using over 1066 rainfall stations (Parajka et al., 2007). Information on hydrogeology, land use, and soil types was also used. In order 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.

3. ESTIMATING FLOODS FOR CROSS SECTIONS WHERE FLOOD PEAK DATA ARE AVAILABLE

As mentioned above, three types of information were used in addition to the local flood peak data to assist in the flood frequency estimation. These were temporal information, spatial information and causal information expansion to explore the flood generation processes. The three types of information were combined for all catchments where such information was available. The use of these three types of information is illustrated here by one example in the north of Austria, the Kamp catchment at Zwettl (Figs. 2 and 3). Fig. 2 shows the flood frequency curve based on the standard flood peak data used by the Hydrographic Service, which consists of the 1951-2004 series (full circles). There is an obvious outlier, i.e., the 2002 flood, which does not conform to the rest of the flood peak sample. Using standard plotting positions (such as the Weibull plotting position), the outlier plots on a return period of about 50 years. However, it is clear the return period of the 2002 flood was much

larger than this. In order to assist in the hydrological assessment of the return period of the 2002 flood, the flood record has been extended by reconstructing the available stage data at Zwettl. These data extend the record back to 1894 and the resulting plotting positions are shown as plusses. The record can be further extended to the past by the use of historic flood information (the 1655, 1803 and 1829 floods) as back-calculated from archival information and flood marks. Using the historic data makes the 2002 flood much more consistent with the other flood data and gives an approximate return period of 500 years for the 2002 flood. The uncertainty bounds of the flood frequency curve hence are much narrower if the temporal (historical) information is used (light grey in Fig. 2)

Spatial information was used by comparing the flood estimates at the Kamp with the flood estimates at neighbouring stream gauges. A number of methods were used, including a geostatistical

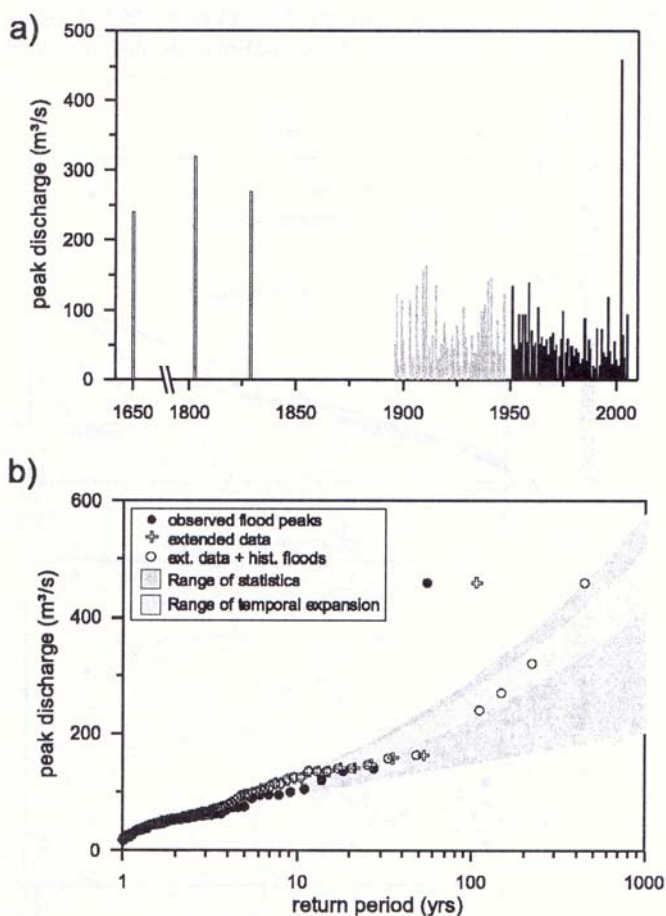


Fig. 2 Flood frequency curves with different types of temporally expanded information (see text). Kamp at Zwettl, 622 km^2 catchment area.

method (Skfien et al., 2006), regressions and graphic methods such as discharge-area diagrams. The solid line in Fig. 3a shows the regional flood frequency estimate from the geostatistical method. It is slightly higher than what the local plotting positions (full circles) indicate. Causal analysis was also used to further constrain the flood frequency graphs. For example, the Gradex method (Merz et al., 1999) which estimates flood probabilities from rainfall probabilities was used. As the method for the Austrian case is based on daily precipitation data, the method is only applicable to those catchments where the response time is on the order of a day. This is the case for the Kamp. The Gradex estimate (using a rainfall station in the region) is shown as a dashed line and indicates a sharp increase beyond the threshold return period of 30 years. This increase is consistent with the presence of an outlier. In fact, the soils in the Kamp are sandy with large infiltration capacities, but beyond a threshold (which is on the order of 80 mm), the soils are saturated, and runoff generation starts abruptly (Blöschl et al, 2007; Blöschl, 2008). Fig. 3 also illustrates another causal analysis. Fig. 3b shows

the event runoff coefficients of flood events plotted against the return periods of the associated flood peaks. Quite clearly, the runoff coefficients increase with the return periods. This corroborates the non-linearity present in the Kamp catchment (Komma et al., 2007). In terms of the flood estimates, the combined information (temporal, spatial, causal) suggests that the 100-year flood is about $0.4 \text{ m}^3/\text{s}/\text{km}^2$ or $250 \text{ m}^3/\text{s}$.

4. ESTIMATING FLOODS FOR CROSS SECTIONS WITHOUT FLOOD PEAK DATA

The spatial analysis of the flood data was based on the flood moments, i.e., the mean (MAF), the coefficient of variation (CV) and the skewness (CS) of the annual floods. In order to reduce the effect the catchment area may have on the MAF, the specific flood discharges have been standardised to specific discharges of a hypothetical catchment area α according to

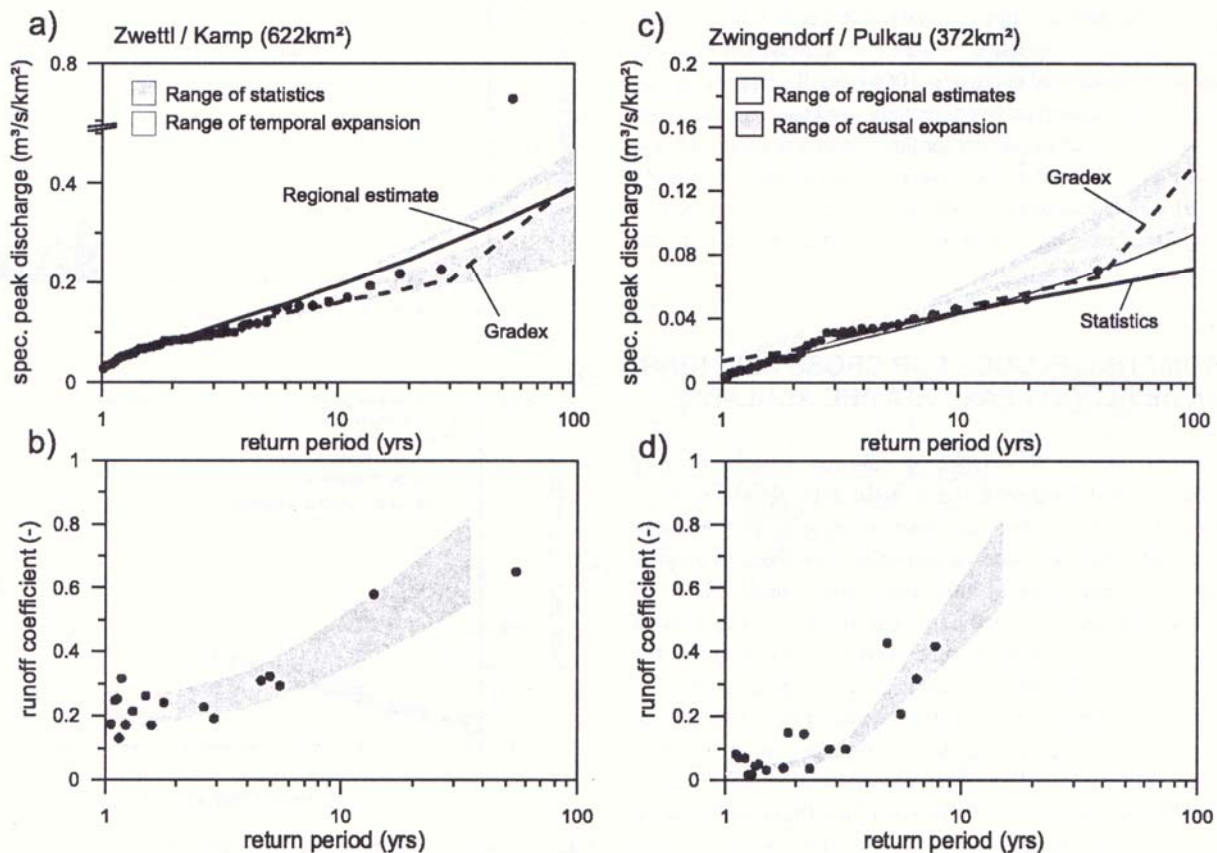


Fig. 3 (a) Flood frequency curves with regional information and causal information (Gradex). (b) Runoff coefficients of the associated flood events plotted against the return periods of the flood peaks. Kamp at Zwettl, 622 km² catchment area.

$$MAF_{\alpha} = MAF_A \cdot A^{\beta} \cdot \alpha^{-\beta} \quad (1)$$

where MAF_{α} is the specific mean annual flood discharge for a hypothetical catchment of an area $\alpha = 100 \text{ km}^2$ and MAF_A is the observed specific mean annual flood of a catchment of area A (km^2). The exponent β was found by a regression of the MAF and catchment area in a semi-logarithmic plot and ranged between 0.18 and 0.3 for various regions in Austria. The three moments were interpolated in a first step by a geostatistical method known as Top-kriging. Top-kriging takes both the catchment area and the distance along a stream network into account (Skfien 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 the record length. Stations with short records can therefore be used in the regionalisation but get smaller weights than stations with long records. A number of additional controls were considered by estimating the mean annual flood MAF for catchments with stream gauges, in particular, mean annual

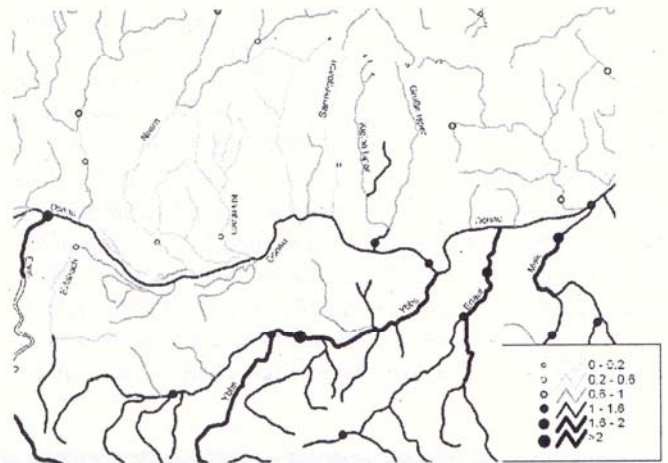


Fig. 4 Estimates of the normalised specific 100-year flood from Top-kriging (shown as the width of the stream network) in the Danube (Donau) region in Upper Austria. The estimates of the gauged catchments are shown as circles. Units are in $\text{m}^3/\text{s}/\text{km}^2$. The width of the domain shown is about 60 km.

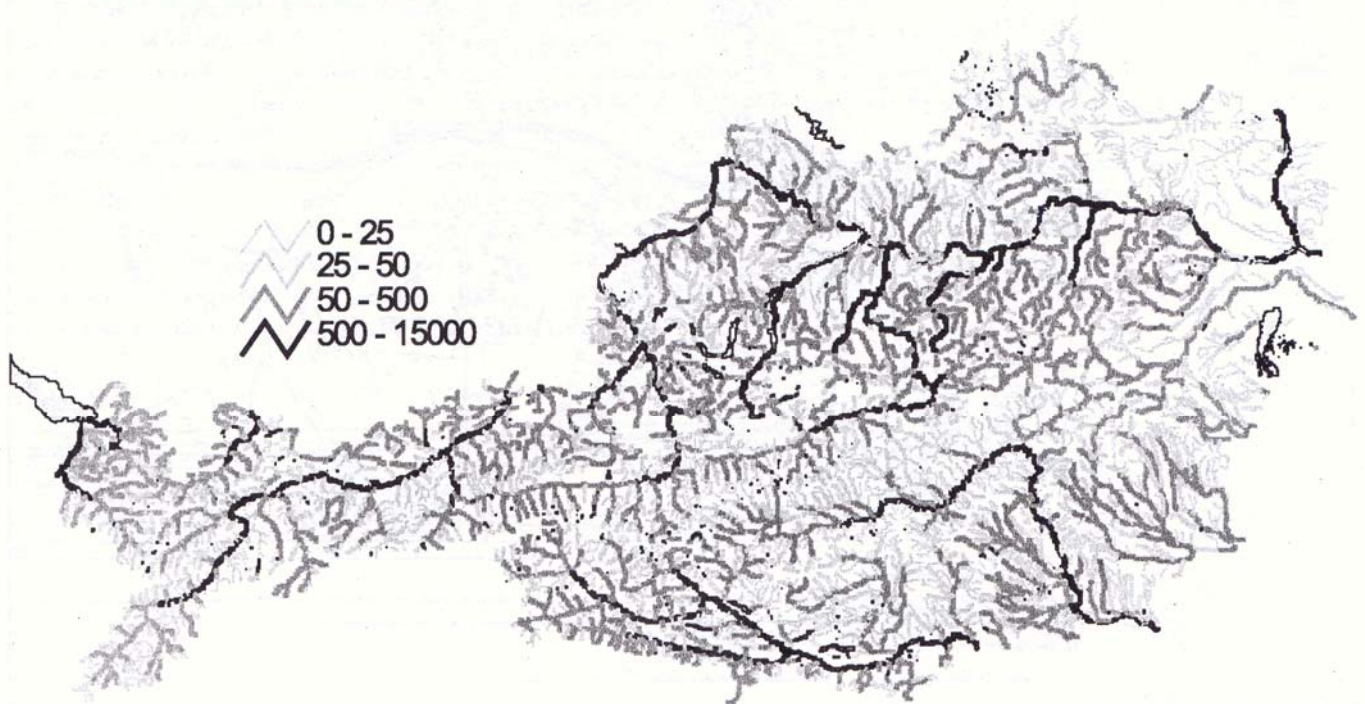


Fig. 5 100 year flood (m^3/s) for 26,000 km of streams in Austria as a result of the estimation procedure.

precipitation and the FARL index. 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 the nodes of the stream network. As an example, the normalised specific 100-year flood (Eq. 1) for the Danube (Donau) region in Upper Austria is shown in Fig. 4. There is a high variability in the specific flood discharges of the tributaries. The tributaries from the North (e.g., Naarn, Klambach, and 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 the catchment area and the nested structure of the river network into account.

In order to account for local particularities of catchments, an iterative regionalisation approach was adopted. The estimates of Top-kriging 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. The regional flood maps were compared against geological and soil information and flood types (Merz and Blöschl, 2003) as well as information on hydraulic structures and water transfers. If local behaviour was

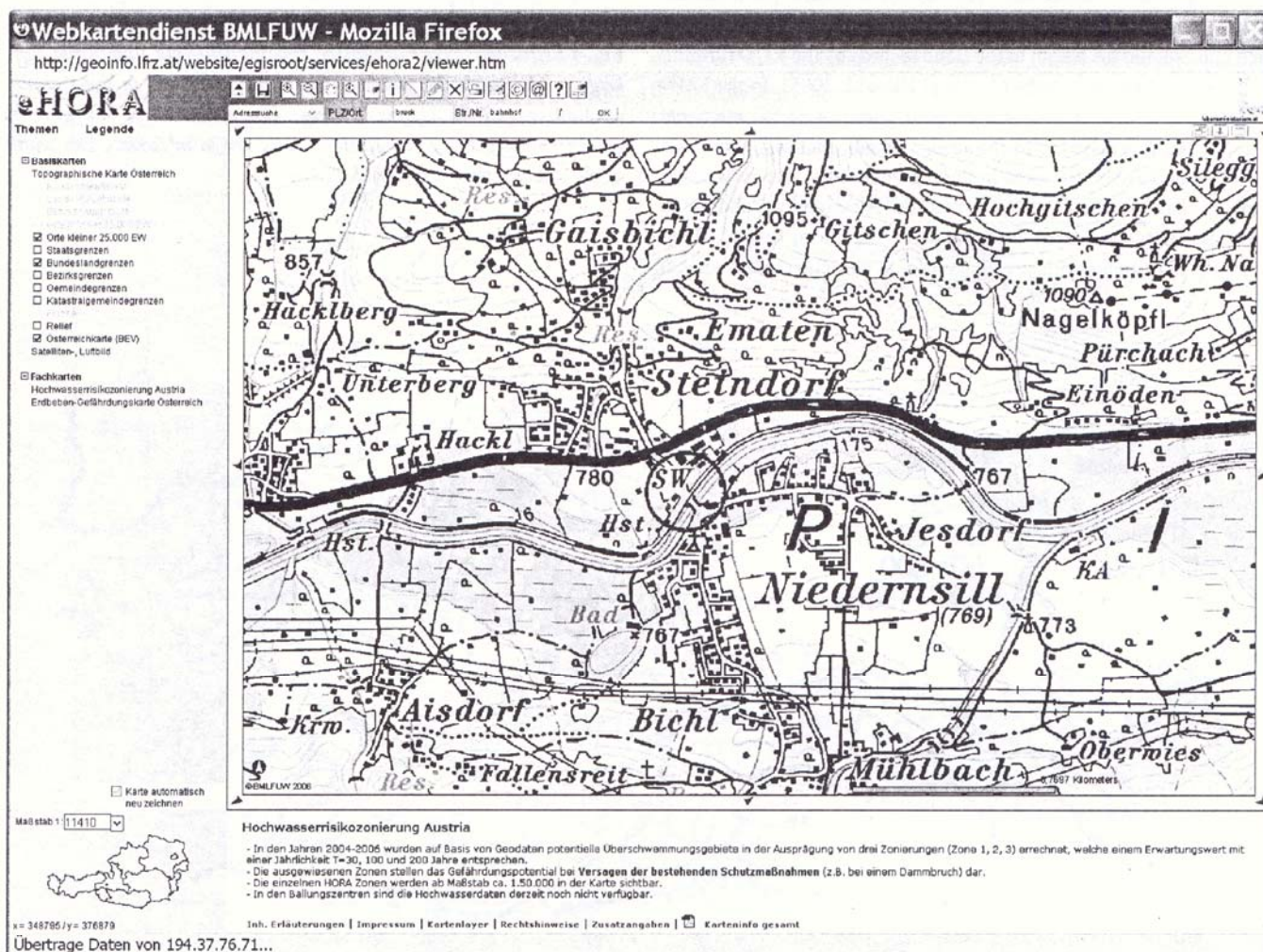


Fig. 6 Screen shot of the flood risk maps at www.hochwassersisiko.at. The grey area in the centre of the map is the potentially flooded area associated with the return period of a flood peak of 100 years.

deemed not to be captured by the automatic Top-kriging 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 as the moments estimated from the flood samples, either as regionally representative pilot points or as locally representative pilot points. This allowed an adjustment to the local flood behaviour found by the assessments of the analyst and the staff of the hydrographic services.

5. APPLICATION TO FLOOD ZONE MAPPING AND CONCLUSIONS

The final result of the flood estimation for all of Austria is shown in Fig. 5 for the case of a 100-year flood. Fig. 5 shows a 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 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 borders.

The flood discharges estimated by the method 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 (www.hochwassersisiko.at) with public access. For georeferencing, the internet application shows maps or areal photographs, depending on the 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. An example of a screen shot is shown in Fig. 6 for part of the Salzach river. The grey area in the centre of the map is the potentially flooded area associated with a return period of a flood peak of 100-years. The flood zone maps are widely used by the Austrian public through access to the web page. They are also used by the Austrian Association of Insurance Companies and the Austrian Ministry of Agriculture, Forestry, the Environment and Water Management in the context of the European Flood Directive. Equally important, the flood estimates obtained by the methods summaries in this paper are the basis for obtaining design flood estimates by the hydrographic services. Depending on the application the flood estimates are used as is or, alternatively, the estimates are combined with more detailed studies such as rainfall-runoff analyses.

6. ACKNOWLEDGEMENTS

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