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Flood frequency hydrology: 1. Temporal, spatial, and causal expansion of information

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[1] The hydrological literature on flood frequency analysis in the past has placed undue emphasis on solving the estimation problem. In this paper we argue that much better use should be made of the wealth of hydrological knowledge gained in the past century and that it is essential to expand the information beyond the flood sample at the site of interest. We suggest that the expansion of information can be grouped into three types: temporal, spatial, and causal. We present a number of examples from Austria to illustrate the rich diversity of flood processes that are often site specific and difficult to capture by formal methods. On the basis of these examples, and the expansion of information, we illustrate that hydrological reasoning can provide diagnostic findings that give guidance on how to adjust quantitative estimates from formal methods to more fully capture the subtleties of the flood characteristics at the site of interest. We believe that this approach gives a more complete representation of flood processes at a given site than the existing formal methods alone and propose the term "flood frequency hydrology," as opposed to flood frequency statistics, to reflect the focus on hydrological processes and hydrological reasoning.

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1. Introduction

[2] *Fuller* [1914] was among the first to apply probability principles to flood problems. The aim was to replace the earlier design flood procedures, such as envelope curves and empirical formulae, by more objective estimation methods. When longer flood records became available by the middle of the twentieth century and with further theoretical developments such as the extreme value theory of *Gumbel* [1941], the method rapidly became what *Klemeš* [1993] termed "the standard approach to frequency analysis." In essence, it consists of fitting distribution functions to ordered sequences of observed flood peaks and extrapolating the tails of the distribution to low exceedance probabilities. During the second half of the twentieth century, the method has been refined in many ways. In the main, the focus has been on solving the estimation problem. The type of distribution function has been the subject of great debate as has been the parameter estimation methods. Over the years, varieties of the method of moments, maximum likelihood and L-Moments have been proposed and alternative, nonparametric methods have been developed as well [*Bobée and Rasmussen*, 1995]. Regional frequency analysis, similarly, has evolved over the decades including methods such as the index flood method, the region of influence approach, and regressions between flood characteristics and catchment characteristics. The latter method has become particularly popular with the proliferation of geographical information systems which can estimate catchment characteristics with much ease.

[3] There are, however, a number of intrinsic weaknesses of the standard approach most of which relate to the problem that the available flood peak sample tends not to be representative of the future flood behavior one strives to capture. The available flood records are often too short to reliably extrapolate to large return periods, in particular in small basins. This issue is exacerbated by changing catchment and stream conditions (such as land use change and construction of levees). Perhaps more importantly, extreme floods tend to occur in clusters with long periods without significant floods which increases the chance that the available flood sample happens to be in a period of untypical flood conditions. Small and moderate floods in a sample may or may not be representative of extreme floods as the causing mechanisms may change with the magnitude of the event. Catchment attributes used to estimate flood characteristics at ungauged sites may not be representative of the underlying processes as soil hydrological processes are not very well understood at the regional scale. Also, catchments tend to be very heterogeneous in space so regional transposition may or may not be justified. Finally, observed flood peaks are subject to considerable error as the measurement error of discharge tends to increase with discharge owing to a number of reasons.

[4] These weaknesses are fully appreciated in the literature. It is hence clear that "statistical analysis alone will not resolve all flood frequency problems" [*U.S. Geological Survey*, 1982]. There is a need for hydrological reasoning in the flood frequency estimation procedure. The introduction of part 3 of the Flood Estimation Handbook [*Institute of Hydrology*, 1999] concludes with "the best flood estimates

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will combine the effective use of flood data and software with a strong dose of hydrological and statistical judgement, ...'' and, as early as 1936, *Slade* [1936] stated ''... the statistical method, in whatever form employed (graphic or analytical), is an entirely inadequate tool in the determination of flood frequencies. When used in conjunction with nonstatistically inferred data, however, it may attain a high order of precision.''

[5] Although most hydrologists would agree on the importance of hydrological reasoning in flood frequency estimation, most publications in the hydrological literature have focused on solving the estimation problem. Very little guidance is given on what exactly the hydrological reasoning should be based on. Also, very little evidence is given of the rich diversity of hydrological processes that control flood frequency behavior and of how these processes can be captured by formal methods. *Klemeš* [1993] summarized the concerns: ''The main point of my criticism has been the apparent confusion about the nature of the problem which has led to the pursuit of high mathematical rigour which, at best, is of marginal importance in this context, while neglecting the important matters such as the hydrological information content of the data and the practical decision-oriented (rather than theoretical-statistical) purpose of the analysis,'' and flood frequency analysis ''contributed merely to the art of curve fitting and to the theory of small samples from known distributions rather than to its original aim, i.e., to a better information about the probabilities of extreme hydrological events and thus to better design and planning decisions.''

2. Flood Frequency Hydrology

[6] The hydrological information content of the data is indeed the important matter. And again quoting *Klemeš* [1993]: ''If more light is to be shed on the probabilities of hydrological events, then it will have to come from more information on the physics of the phenomena, not from more mathematics.'' In this paper we argue that, in flood frequency analysis, much better use should be made of the wealth of hydrological knowledge gained in the past century. While the flood peak sample is an important source of information there may exist numerous other sources that are hydrologically relevant and these should be used to obtain more accurate estimates. It is hence essential to expand the information beyond the flood sample at the site of interest. We suggest that the expansion of information can be grouped into three types: temporal, spatial and causal expansion.

[7] Temporal information expansion is directed toward collecting information on the flood behavior before or after the period of discharge observations. Spatial information expansion is based on using flood information from neighboring catchments to improve flood frequency estimates at the site of interest. Causal information expansion analyses the generating mechanisms of floods in the catchment of interest.

[8] It is true that on each of these types of information expansion, methods have been proposed in the literature. Formal methods exist on combining historical flood data and palaeofloods with available flood records [e.g., *Benito and Thordycraft*, 2005] which would be considered temporal information expansion. Methods of regional flood frequency analysis [e.g., *Dalrymple*, 1960; *Cunnane*, 1988; *Bobée and Rasmussen*, 1995; *Hosking and Wallis*, 1997; *Merz and Blöschl*, 2005] would be considered spatial information expansion. Finally, the derived flood frequency approach [i.e., *Eagleson*, 1972, *Fiorentino and Iacobellis*, 2001; *Sivapalan et al.*, 2005] would be considered causal information expansion.

[9] All of these methods are, of course, useful but we suggest two changes in the focus. First, there are subtleties in the hydrological processes that are difficult to capture by formal methods but may be amenable to hydrological reasoning. There is a rich diversity of hydrological processes that are relevant to flooding and these are often site specific. The hydrological reasoning will hence also be site specific. Second, we believe it is important to combine all relevant hydrological information at a site. Obviously, available information will differ from catchment to catchment and so will be the way the various pieces are to be combined. Some sources of information will be quantitative while others will be proxy data or indicators but they may contain valuable information on some aspects of the floods. The combination of these data will provide diagnostic findings that give guidance on how to adjust quantitative estimates from formal methods to more fully capture the subtleties of the flood characteristics at the site of interest. We hence believe that this approach gives a more complete representation of flood processes at a given site than the existing formal methods alone.

[10] In the spirit of a shift away from solving the estimation problem to hydrological understanding we propose the term ''flood frequency hydrology'' as opposed to flood frequency statistics. The proposed term reflects the focus on hydrological processes and hydrological reasoning. Instead of using methods that are seemingly rigorous in statistical terms but are based on limited information we suggest that expanded information along with hydrological reasoning will provide a more complete understanding of the flood characteristics of any one catchment. As some of this information is not amenable to formal methods, a less formal but more informative reasoning is in place. The basic principle is to incorporate a maximum of relevant information from different complementary sources and their systematic combination.

[11] The aim of this paper is to illustrate the rich diversity of flood processes that is not fully appreciated by formal methods. We give examples of the three types of information expansion and illustrate how the information can be used in diagnostic analyses to assist in hydrologically based flood frequency estimation. The examples provided here are a small sample of the variety of processes that may be encountered in different parts of the world but they are sufficiently diverse, we believe, to demonstrate the richness of processes. In a companion paper [*Merz and Blöschl*, 2008] we show, again by example, how the different sources of information can be combined in a flood estimation setting. The examples are taken from an extensive Austrian case study [*Merz et al.*, 2008]. The hydrological characteristics of Austria, in a flood context, are summarized by *Merz and Blöschl* [2003].

3. Temporal Information Expansion

[12] Temporal information expansion puts the observed flood sample into the wider context of the hydrological history of the catchment. This is particularly important if the

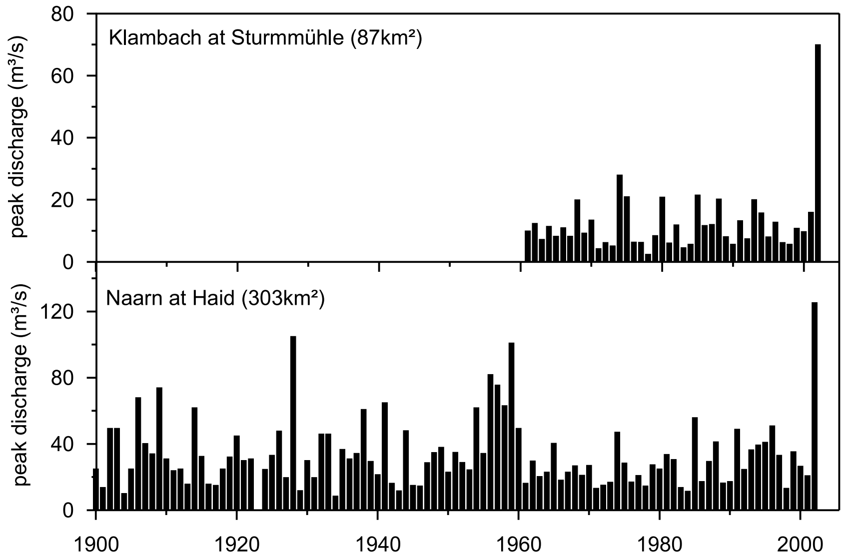

Figure 1. Time series of observed maximum annual peak discharges of (top) Klambach at Sturmmühle (87 km^2 catchment area) and (bottom) Naarn at Haid (303 km^2 catchment area).

flood records are short as is often the case in small catchments. The idea of temporal information expansion is that the history gives guidance on the future flood behavior to be expected. Most importantly, the longer series may help locate whether the available short record contains decades of untypical low or high flood conditions.

[13] The most favorable case, of course, is if a stream gauge with a much longer record is located close to the site of interest. An example is shown in Figure 1. For the Klambach at Sturmmühle (Figure 1, top) 42 years of observation are available (from 1961 to 2002). The striking point in the flood sample is the large flood in 2002 with about 70 m^3/s peak flow. This outlier results in the sample statistics of a mean annual flood (MAF) of 12.5 m^3/s, a coefficient of variation (CV) of 0.86 and a skewness (CS) of 3.92 which is large. For the same time period, the neighboring catchment Haid at the river Naarn shows a similar flood regime of small annual flood peaks for the period 1961 to 2001 and a much larger single flood event in 2002. For this 42-year time period the sample flood moments at Haid are: MAF = 29.5 m^3/s, CV = 0.64 and CS = 3.35m^3/s. At Haid, flood data are available from 1900 which helps put the 42-year period into context. Much larger floods, similar to the 2002 event, have occurred regularly before 1961. The sample flood moments at Haid for the period 1900 to 2002 are MAF = 34.2 m^3/s, CV = 0.62 and CS = 1.82. Assuming that at Sturmmühle the flood regime before 1961 was similar, the flood moments can be adjusted. In particular, the CS would have to be reduced by a factor of nearly 2. An interesting point, from a hydrographic perspective, is the beginning of the flood observations at Klambach after a period of high floods between 1956 and 1960 in the region (see time series at Haid). It appears that the gauging station was installed in response to destructive floods in that period. This may be a general pattern which may introduce biases in the flood estimation process.

[14] Formal methods, termed climate corrections, are available that can be used to adjust the short flood time series if longer series are available in the region. For example, in the Flood Estimation Handbook [*Institute of Hydrology*, 1999] a method of adjusting the median of the observed flood sample for climate variability is proposed. However, there are cases where adjusting the median is not the most efficient correction. In the example shown here, one would clearly adjust the skewness, as it is a single event that causes the main deviation between the two records of different length.

[15] If no long flood records in the region are available, an alternative is to use indices or proxy data that are indirectly related to the flood magnitudes in the past. While indices are much less accurate than runoff data, the time period over which they are available can be enormous, depending on the nature of the data. Types of data include paleoflood information where sediment deposits are analyzed, that can date back over millennia [*Benito and Thordycraft*, 2005]. Historical flood information can date back over centuries and usually gives evidence of the water level during large floods [*Brázdil and Kundzewicz*, 2006]. Flood marks on buildings are the most common piece of information. Alternatively, archival information may be available that relates the water levels to some datum (bridges, streets, buildings), that can be identified in the present situation. Other sources give evidence of the impacts of the flood event such as the accounts analyzed by *Rohr* [2006] on the expenses for flood-related repairs of a bridge in the 16th century. Even if the exact determination of discharge from the proxy data is difficult, they can provide orders of magnitude of flood flows that can be extremely useful for adjusting plotting positions of the observed flood sample.

[16] An example of using historical data for flood frequency estimation is shown in Figure 2 for the city of Villach at the Drau river in southern Austria. Runoff has been observed from 1951 to 1981. *Rohner et al.* [2004] provides information on historical flood events for the city of Villach. From flood marks and historical photos (Figure 2, top left and top middle) of the Lederergasse, which is close to the gauging stations, water level of historical events can

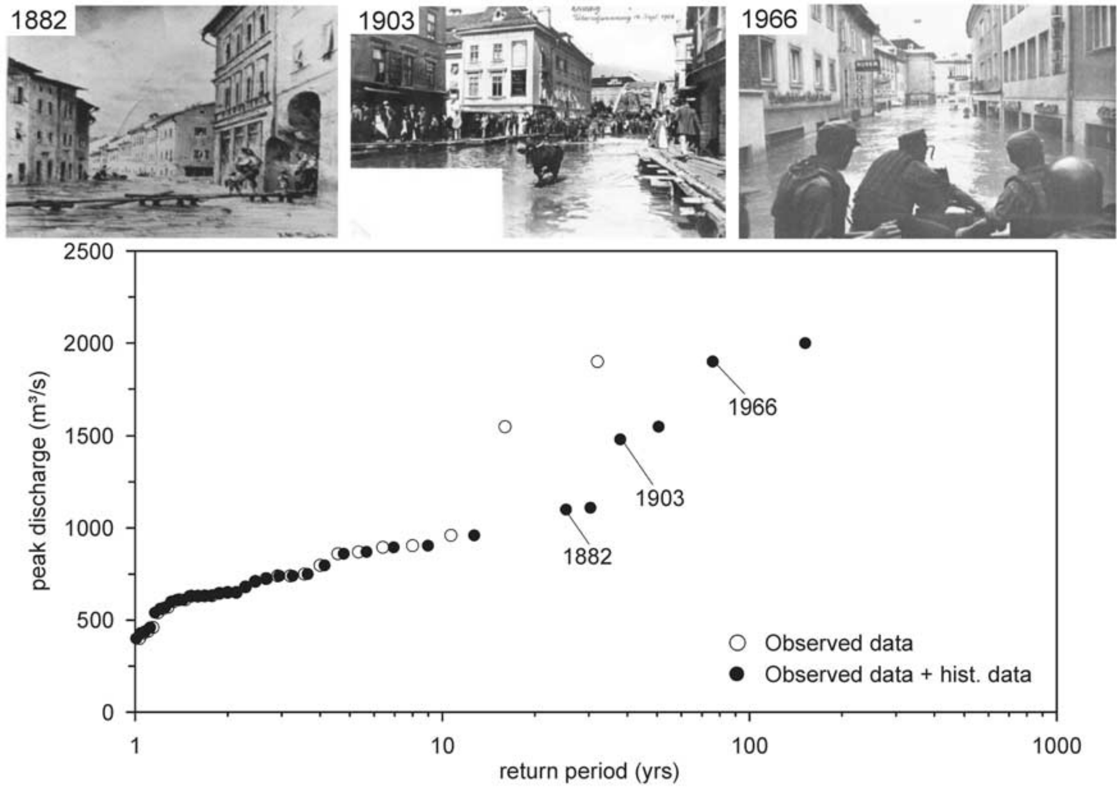

Figure 2. (top) Painting and photographs of historical (1882 and 1903) and observed flood (1966) water stages at the Lederer Gasse near the Drau cross section at Villach. (bottom) Flood frequency plot of the Drau at Villach based on observed flood data (open circles) alone and observed and historical flood data (black circles) derived from flood marks and photographs.

be assessed. By comparison with the water level of observed flood events (e.g., event 1966, Figure 2, top right) flood discharges can be reconstructed. Plotting positions (Figure 2, bottom) of the flood sample plus the censored data using equations 18.6.11 and 18.6.12 of *Stedinger et al.* [1993] are shown as solid circles. In comparison the plotting positions of the flood sample alone, using Weibull's formula, are shown as open circles. The largest flood in the sample was the event of 1966 which, according to the plotting position formula, is associated with a return period of 32 years. If one incorporates historical information, the plotting position can be adjusted to a return period of about 80 years. If one ignores historical flood data the flood frequency curve would overestimates the flood flows at large return periods. In this case, hydrological reasoning has been used to make an informed guess about the discharge of the historical floods, while a formal method [*Stedinger et*

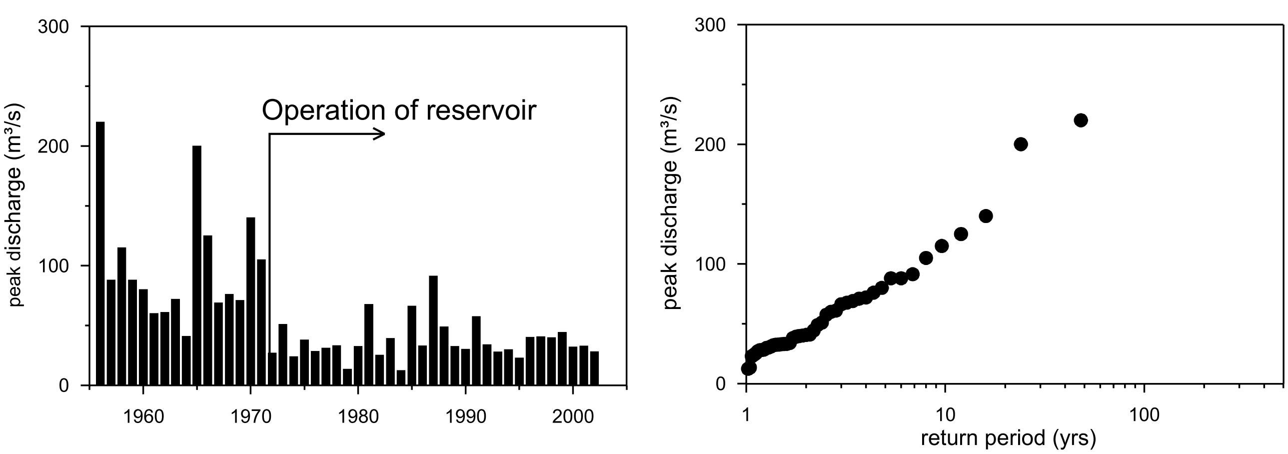

Figure 3. (left) Time series of observed maximum annual peak discharges of the Zemmbach at Sausteinaste (225 km^2 catchment area). The upstream Schlegeis reservoir was built in 1972. (right) Flood frequency plots of the Zemmbach at Sausteinaste.

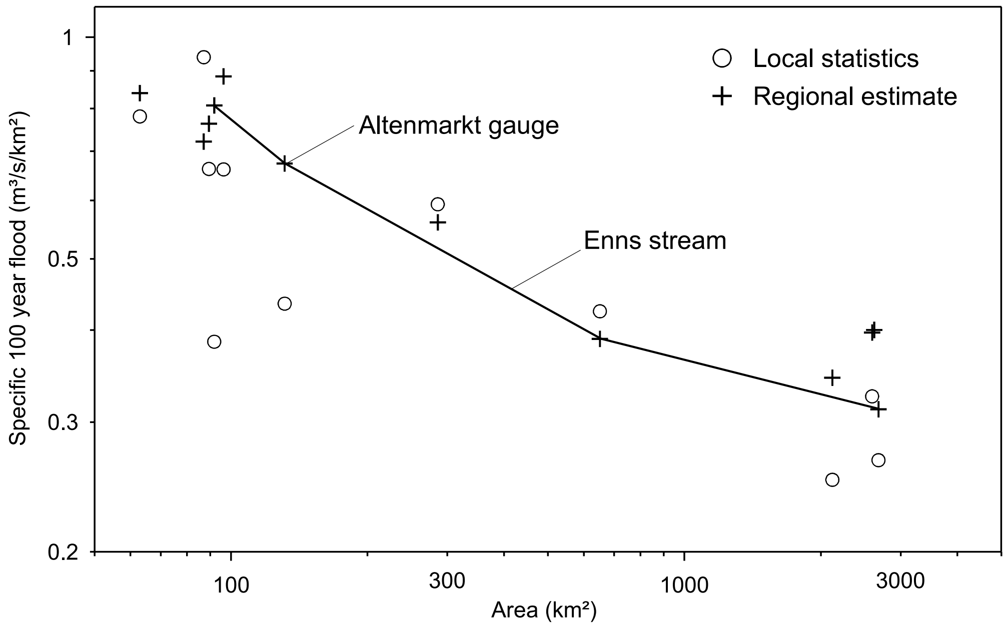

Figure 4. Discharge-area diagram of the upper Enns valley. Specific 100-year flood discharges derived from locally observed data are shown as open circles. Regional estimates using flood data from neighboring stations are shown as plusses.

al., 1993, equations (18.6.11) and (18.6.12)] has been used to combine this information with the flood sample.

[17] Notwithstanding the value of temporal information expansion there exist cases where the expanded information may indeed be misleading. This is so if the past is not a faithful indicator of the future, i.e., if the past is not representative of the design period for which one is to estimate the floods of a given probability. There are a number of reasons why changes in the flood characteristics over time may occur, including land use change, and construction of levees, dams and retention basins. Another example are ice jam floods in the Austrian part of the Danube. Some of the largest floods that occurred in the 19th century were caused by ice jams. Owing to the extensive operation of hydropower plants the water temperature of the Danube has increased and so the frequency of ice jams has decreased drastically. Also, the dams tend to reduce the transport of ice floats and ice breakers are used in some parts of the Danube. Analysis of ice jam floods will hence not be a reliable indicator of future flood occurrence.

[18] An example of the effect of reservoir construction is shown in Figure 3. The decrease in the flood magnitudes after the Schlegeis reservoir was built in 1972 is quite dramatic in Figure 3 (left). The reservoir has a volume of 127×10^6 m^3 with a catchment area of 58 km^2 while the downstream gauge shown in Figure 3 has a catchment area of 225 km^2. The flood event volumes of the largest floods were on the order of 25×10^6 m^3. The reservoir hence has significant potential to reduce flooding which is also clear from the record. In this case, the flood peak that will leave the reservoir will depend on the free volume which, in turn, depends on the reservoir management. This means that a flood of a given return period downstream of the dam is not uniquely defined. In Austria the power market has changed in the 1990s to which the reservoir operation has adjusted so, in addition to the changes in 1972, changes in the 1990s are likely. There are formal methods that account for reservoir effects, including detailed flood routing methods, and simplified methods such as the FARL index [*Institute of Hydrology*, 1999] that only accounts for the catchment areas. While the FARL index was found to be a useful first approximation to retention effects of reservoirs in Austria, it adjusts the median flood, so cannot represent the more complex patterns one would obtain in the example shown here. It is clear that the reservoir will not only affect the median but higher moments as, for extreme floods, the free reservoir capacity may be exhausted leading to very little peak reduction. It is also interesting that the changes in the flood regime are not apparent in the flood frequency curve (Figure 3, right). Simply fitting a distribution function to the flood sample would overestimate the flood peaks. This example illustrates the trade-off between the merits of temporal information expansion and possible trends in flood behavior that need to be assessed by hydrological judgment.

4. Spatial Information Expansion

[19] Spatial information expansion is based on using flood information from neighboring catchments to improve the at-site flood frequency estimation. Additionally, spatial information expansion can be used for estimating flood frequency in ungauged catchments. The underlying assumption of both applications is that space can be substituted for time after suitable transformation. This is the case if the regional trend is indeed representative of the local conditions, in some way. Often, formal statistical tests are used to ascertain whether a region can be considered homogeneous [see, e.g., *Hosking and Wallis*, 1997]. Three examples of spatial information expansion are given here to illustrate the strengths of spatial information expansion but, at the same time, to illustrate that there exist subtleties that cannot easily be captured by formal methods.

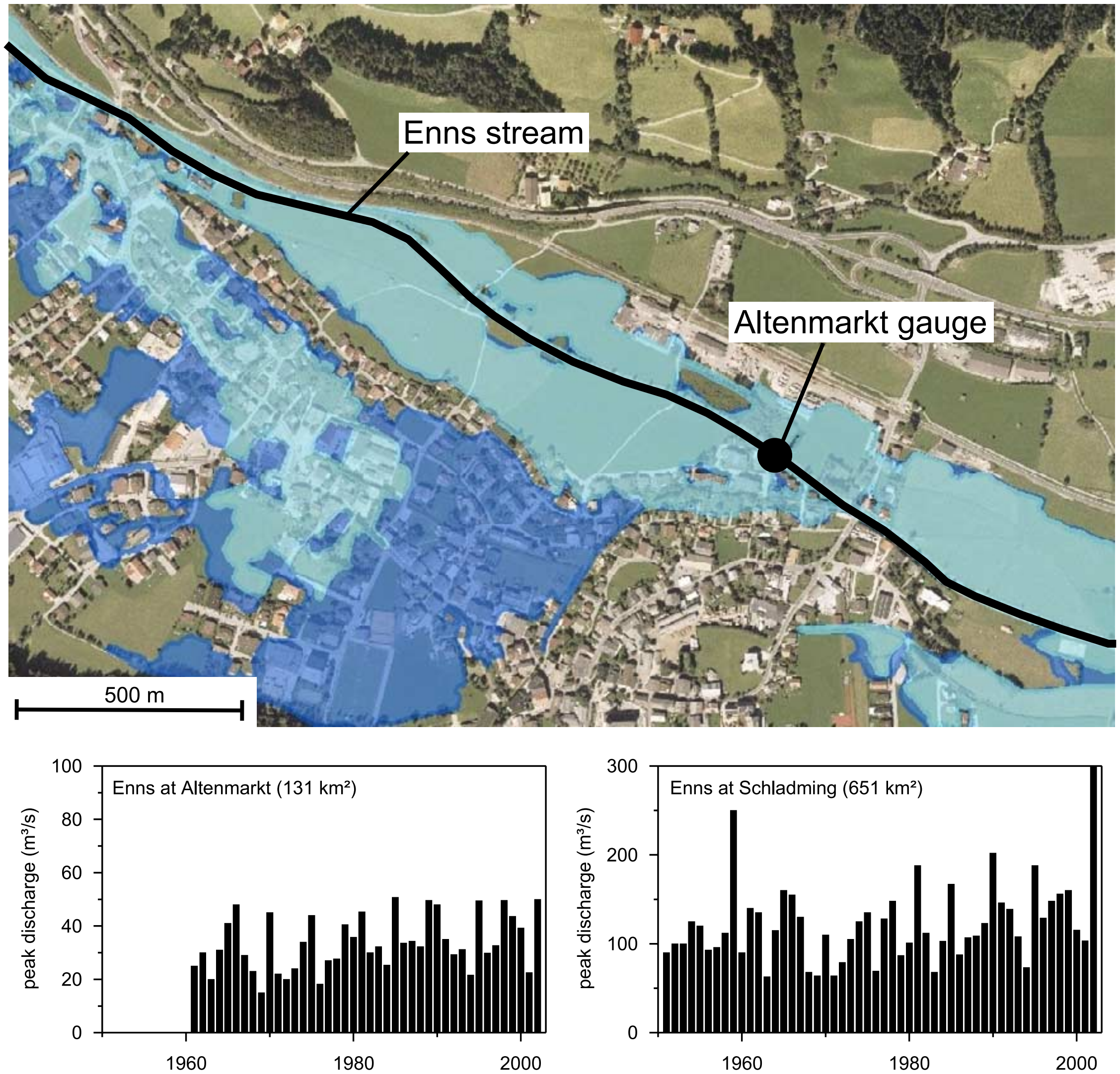

Figure 5. (top) Flood risk maps from the HORA project (www.hochwasserrisiko.at) of the Enns river at Altenmarkt. Inundation areas of 30- and 100-year floods are shown in light blue and dark blue, respectively. (bottom) Times series of observed maximum annual peak discharges of (left) the Enns river at Altenmarkt (313 km^2 catchment area) and (right) the Enns at Schladming (651 km^2 catchment area). Owing to inundation effects the peak discharges at Altenmarkt are truncated at about 50 m^3/s.

[20] The first example is the flood frequency estimation at Altenmarkt at the upper Enns river. In Figure 4, the specific 100-year discharges at Altenmarkt and other gauges in the area have been plotted against catchment area. The open circles represent the estimates from the local flood samples alone using the GEV distribution and the method of moments. In addition, regional estimates for the same location have been plotted in the graph that were obtained from the neighboring catchments by top-kriging, without use of the local flood data (pluses). Top-kriging [*Skøien et al.*, 2006] is a geostatistical estimation approach that takes into account river network structure and catchment area. The striking point at Altenmarkt is that the local estimate is much lower than the regional estimate. An analysis of the catchment characteristics such as topography, geology and rainfall did not point to any major differences from the rest of the catchments in the region. However, interviews with the local Hydrographic Service indicated that the stream gauge tends to get inundated during floods and, apparently, the data have not been corrected. These findings can be corroborated by various types of analysis. For example, the pattern of the flood time series (Figure 5) suggest that the distribution is truncated around 50 m^3/s which is the flow at which inundation into the floodplain occurs. This is particularly apparent when comparing the Altenmarkt time series to another gauge in the area (e.g., Enns at Schladming) which shows a similar pattern but without the peaks truncated. An alternative source of information are the flood risk maps from the HORA project (www.hochwasserrisiko.at) which indicate widespread flooding in the area (Figure 5). These are both sources of information that cannot be easily formalized. However, it is essential for some sort of correction to be applied to obtain a more realistic estimate of the total flow at that cross section. In the example shown here, the 100-year discharges were corrected from 58 m^3/s to 86 m^3/s on the basis of the characteristics of the flood

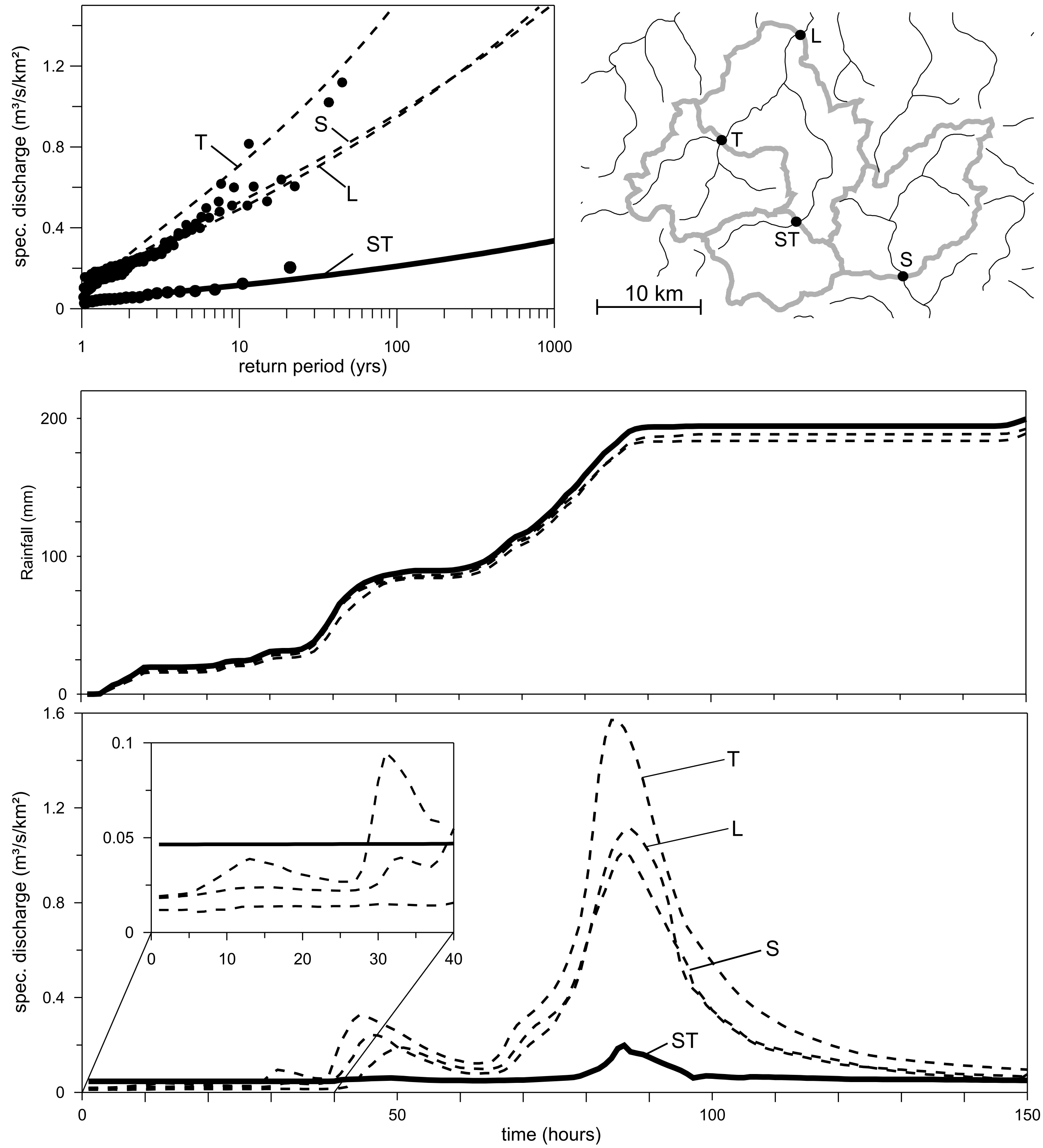

Figure 6. Flood frequency plots of (top left) the Unrechtstraisen at St. Aegyd (ST) (54 km^2 catchment area) and (top right) neighboring catchments (Traisen at Türnitz (T) (103 km^2 catchment area), Traisen at Lilienfeld (L) (333 km^2 catchment area), and Schwarza at Schwarzau (S) (128 km^2 catchment area)). (middle) Hyetographs and (bottom) hydrographs of the flood event 4 July 1997 to 10 July 1997.

samples in the area, in particular those of the upstream and downstream gauges.

[21] A second example of spatial information expansion is the flood runoff of the river Unrechtstraisen at St. Aegyd (54 km^2) in northern Austria. Flood statistics indicate that the flood discharges at St. Aegyd are only about 20% of those of the neighboring catchments (Figure 6, top left; St. Aegyd is labeled as "ST"). A thorough hydrological way of approaching this issue is to analyze the shape of the flood hydrographs for individual events (Figure 6, bottom). The hydrograph in St. Aegyd (thick solid line) is indeed completely different from those of the other catchments (thin dashed lines) although the rainfall (Figure 6, center) in all catchments was similar. The three neighboring catch-

Table 1. Catchment Attributes of St. Aegyd and Neighboring Catchments

	Unrechtstraisen at St. Aegyd	Traisen at Türnitz	Traisen at Lilienfeld	Schwarza at Schwarzau
Label in Figure 6	ST	T	L	S
Catchment area (km^2)	54	103	333	128
Mean topographic elevation (m)	859	810	759	827
Mean topographic slope (%)	32	34	33	26
Maximum channel length (km)	9	12	30	19
Limestone (%)	15	3	5	15
Dolomite (%)	83	47	54	81
Carbonate rock (%)	2	50	39	2
Rendzina (%)	100	100	95	100
Fluisol (%)	0	0	5	0
Forest (%)	87	89	89	92
Grass (%)	12	9	10	7
Mean annual precipitation (mm)	1325	1329	1289	1225

ments (Türnitz (T), Lilienfeld (L), Schwarzau (S)) exhibit an early small runoff peak at hour 45 and a strong increase in runoff between hours 70 to 90, both in response to rainfall. In contrast, St. Aegyd shows no response at hour 40 and a small peak at hour 90. The early phase of the event is important and is shown in the inset graph. It appears that the base flow at St. Aegyd is much larger than that of the other catchments. The combined evidence of the delayed response to rainfall and large base flows suggests that substantial subsurface flows must occur during the event. Indeed, field surveys in the St. Aegyd catchment indicate that local gravel deposits in the valley exist that are sufficiently thick to control the local runoff regime. It would be difficult to capture these processes by formal methods such as multiple regression. For comparison, catchment attributes of St. Aegyd and the neighboring catchments are given in Table 1. Mean annual rainfall, topographic slope, soil types and land use are similar in all four catchments. The geology of St. Aegyd is similar to that of the Schwarzau catchment and consists of larger areas of dolomite than the Türnitz and Lilienfeld catchments. It is the location of the gravel deposits near the stream that produces the retarding effect rather than the total area. This would be difficult to quantify in a general way. The hydrological reasoning, in contrast, confirms that the small flood discharges at St. Aegyd are a consequence of the local catchment characteristics rather than an artifact of the data or the observational window.

[22] A third example of spatial data expansion addresses the effects of storm tracks. Owing to the high variability of elevation, preferential storm tracks in Austria exist and are important for flood occurrence. Storm tracks from North to South are active along the Isel valley in Carinthia in southern Austria [*Moser*, 2006]. Figure 7 shows the topographic elevations of the upper Isel valley region. The region includes the main ridge of the Alps (west – east) with the Großglockner being the highest peak in Austria (3798 m a.s.l.). Table 2 gives the local flood statistics of some of the stream gauges in the area. Although the four highest catchments in the Isel valley (Innergschlöß, Matreier Tauernhaus at Tauernbach, Spöttling at Kalser Bach and Taurer at Teischnitzbach) are similar in terms of their catchment area, elevation, mean annual precipitation, geology and soils, their specific 100-year discharges range from 0.36 m^3/s (Taurer at Teischnitzbach) to 2.20 (Matreier Tauernhaus at Tauernbach). The specific 100-year flood of the Teischnitzbach is only about half of that of the neighboring Kalser Bach. For ease of comparison of catchments of different size, the specific 100-year discharges Q have been normalized by catchment area A to a standard catchment area α = 100 km^2 by

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

where β = 0.33 was obtained from a regional analysis. The differences in the flood discharges can be explained by storm tracks as observed by radar. In the Salzach valley in the North, large and persistent rainfall events due to orographic lifting of northwesterly airflow can occur, while precipitation systems in the Isel valley usually approach from the south. However, the Tauernbach and the Kalser Bach in the upper Isel valley are open to the North, and rainfall events caused by orographic effects can feed the Tauernbach and the Kalser Bach. The Teischnitzbach is much more shaded by the Großglockner massif, so the specific discharges are smaller.

[23] To confirm the effects of storm tracks and topographic shading, the frequency of concurrent flood occurrence in pairs of catchments was calculated. A frequency of 0 means that no floods occurred in the two catchments at the same time while a frequency of 1 suggests that all floods occurred at the same time. In the latter case one can assume that the flood generating atmospheric mechanisms in the two catchments are similar. The frequencies are shown in Table 3 and indicate that about a quarter of all observed flood events in the Salzach valley and at the Tauernbach and Kalser Bach occurred at the same time, while only about 10% of the floods at the Teischnitzbach occur simultaneously with those in the catchments in the north. This confirms that the low flood values of the Teischnitzbach are real and a result of the particular atmospheric patterns in the region. Clearly, this type of analysis is site specific and would be difficult to formalize in a general way. In a similar fashion as for the time domain, these examples also illustrate the trade-off between the merits of spatial information expansion and possible heterogeneities in the flood behavior that needs to be assessed by hydrological judgment.

5. Causal Information Expansion

[24] The third type of information expansion relates to the use of hydrological understanding of the local flood producing factors to improve the flood frequency estimation at a site. Causal information expansion is particularly important in small catchments, both because fewer and shorter records tend to be available than in larger catchments and because the flood processes are more amenable to analysis than in larger catchments where the regional combination of controls can be relatively more important. Flood generation is a highly complex process so, clearly, the flood producing factors will depend on the climatic and the hydrological situation. A number of examples are given here to illustrate the pattern of hydrological reasoning without being exhaustive.

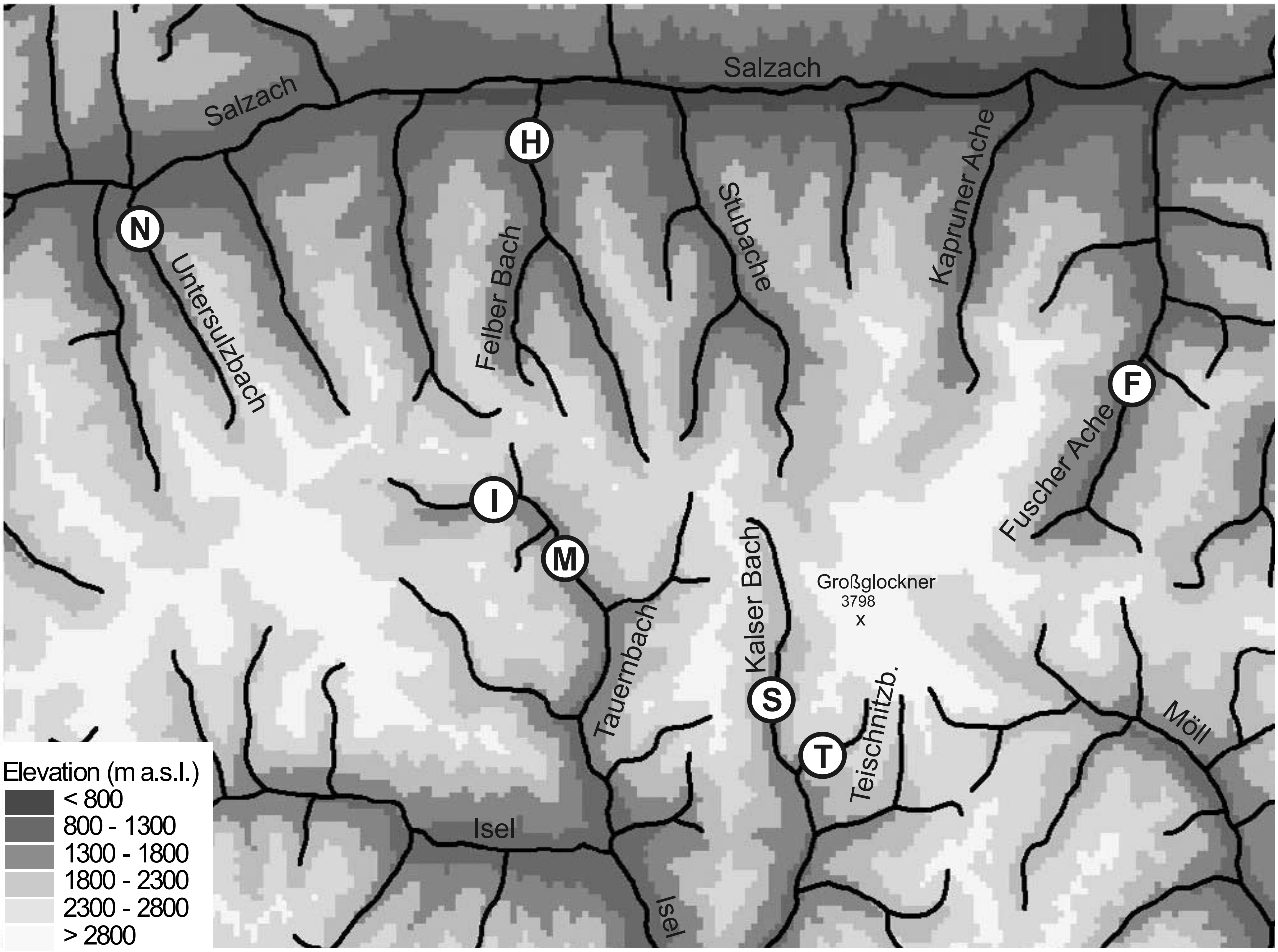

Figure 7. Topographic map of the upper Isel valley. Stream gauges are marked as open circles. N, Untersulzbach at Neukirchen (40 km^2 catchment area); H, Felber Ache at Haidbach (74 km^2 catchment area); F, Fuscher Ache at Ferleiten (61 km^2 catchment area); I, Tauernbach at Innergschlöß (39 km^2 catchment area); M, Tauernbach at Matreier Tauernhaus (60 km^2 catchment area); S, Kalser Bach at Spötlling (47 km^2 catchment area); T, Teischnitzbach at Taurer (14 km^2 catchment area).

[25] Obviously, the main control on river floods in most parts of the world is rainfall. The derived flood frequency approach that estimates flood frequencies from rainfall frequencies has attracted considerable interest in the scientific literature [e.g., *Eagleson*, 1972; *Sivapalan et al.*, 1990; *Rahman et al.*, 2002; *Sivapalan et al.*, 2005] but its impact on practical flood estimation has been much more modest. The main problem is that it is difficult to quantify the joint probabilities of the various controls on the flood frequency curve such as rainfall duration, temporal patterns, multiple events, soil moisture and routing characteristics. Simpler, but statistically less rigorous methods have hence enjoyed some popularity. An example is the Gradex method [*Guillot*, 1972; *Duband et al.*, 1994; *Naghettini et al.*, 1996] that assumes that, beyond a threshold return period, any additional rainfall produces a corresponding increase in runoff without losses. The method avoids the joint probability issue to some degree by combining local flood data with the rainfall statistics. While the statistical assumptions may be the subject of some debate, a number of studies have

Table 2. Flood Characteristics of the Upper Isel Valley[a]

	Untersulzbach at Neukirchen	Felber Ache at Haidbach	Fuscher Ache at Ferleiten	Tauernbach at Innergschlöß	Tauernbach at Matreier Tauernhaus	Kalser bach at Spöttling	Teischitzbach at Taurer
Label in Figure 7	N	H	F	I	M	S	T
Catchment area (km^2)	40	74	61	39	60	47	14
Obs. period (years)	31	47	42	52	52	52	52
Norm. MAF (m^3/s/km^2)	0.37	0.27	0.31	0.78	0.74	0.30	0.17
Norm. Q100 (m^3/s/km^2)	0.72	0.81	0.67	1.84	2.20	0.66	0.36

[a]Mean annual specific flood (MAF) and specific 100-year flood Q100 are normalized to a catchment area of 100 km^2 (equation (1)).

Table 3. Concurrency of Floods in Pairs of Catchments[a]

Stream Gauge	Neukirchen (N)	Haidbach (H)	Ferleiten (F)
Innergschlöß (I)	0.21	0.25	0.34
Matreier Tauernhaus (M)	0.18	0.21	0.30
Spöttling (S)	0.20	0.16	0.29
Taurer (T)	0.09	0.09	0.20

[a]Values: 1 = all observed annual floods occurred on the same day, 0 = none of the floods occurred on the same day (see Figure 7).

indicated that the method can indeed increase the accuracy of flood estimates at large return periods [*Naghettini et al.*, 1996; *Merz et al.*, 1999; *Naulet et al.*, 2005]. Derived flood frequency is particularly appealing if the available rainfall records in the region are much longer than the flood records. In Austria, daily rainfall records, typically, are 100 years while flood records are usually 40 years, and shorter in small basins, so the approach may have some merits.

[26] An example to illustrate the case for the river Trisanna at Galtür is shown in Figure 8. The Galtür catchment (98 km^2) is located in the inner part of the High Alps near the Italian border. The runoff regime of the Trisanna river is typical of Alpine rivers, with low flows during winter and high flows and floods during summer, where snowmelting mainly contributes to increasing the antecedent soil moisture of rain storms. At Galtür, 40 years of flood observations have been assumed to be available for the example (1964–2003). For the nearby rainfall station, Partennen, 72 years of maximum annual daily rainfall are available (1926–1997). These two records are combined by the Gradex method as shown in Figure 8. Rainfall is presented as a transformed variable that involves an areal reduction factor of rainfall and a peak-to-volume ratio of runoff. The threshold return period was set to 25 years. This is a relatively low value which was chosen because of the limited storage capacity of the soils in the catchment. Beyond the threshold return period, the Gradex assumptions imply that the flood distribution is parallel to the transformed rainfall distribution. In this example, the steepness of the flood frequency curve increases beyond the threshold indicating that floods may be more extreme than those that are available in the sample. In this example, the most recent flood (August 2005) has been withheld. The peak flow of that flood was estimated as 150 m^3/s. While the return period of the 2005 flood is difficult to assess, the example demonstrates that the steep tail is certainly a more accurate representation of extreme flood behavior in the Trisanna catchment than if one fitted the flood sample by a standard distribution such as Gumbel (Figure 8). The Gradex method is an example where hydrological reasoning is part of a formal method.

[27] Methods such as Gradex do not explicitly account for runoff coefficients but use the threshold return period as an indicator of the saturation deficit of a catchment. Analyzing the event runoff coefficients may give more detailed insights in the flood processes of a catchment. Some of the event runoff coefficient calculated from runoff data by *Merz and Blöschl* [2006] are used here to illustrate the role of runoff coefficients in flood frequencies. Of particular interest is how the flood generating mechanisms change with the magnitude of the event. This will give guidance on how to extrapolate the flood frequency curve to large return periods.

[28] Two examples of the effect of runoff coefficients on the flood frequency curve are shown in Figure 9. The left graphs relate to the Weißach catchment at Zwing which is located in the West of Austria at the northern rim of the Alps. Owing to orographic enhancement of northwesterly airflows, rainfall is high and persistent with mean annual precipitation of about 2000 mm. The runoff coefficients in Figure 9 have been plotted against the return period of the peaks of the associated flood events. For small events, the runoff coefficients range between 0.4 and 0.9 and, as the event magnitudes increase, the runoff coefficients plot around 0.8. This means that there is a moderate trend of increasing runoff coefficients with return period of the peak flow. As rainfall becomes more extreme, one would not

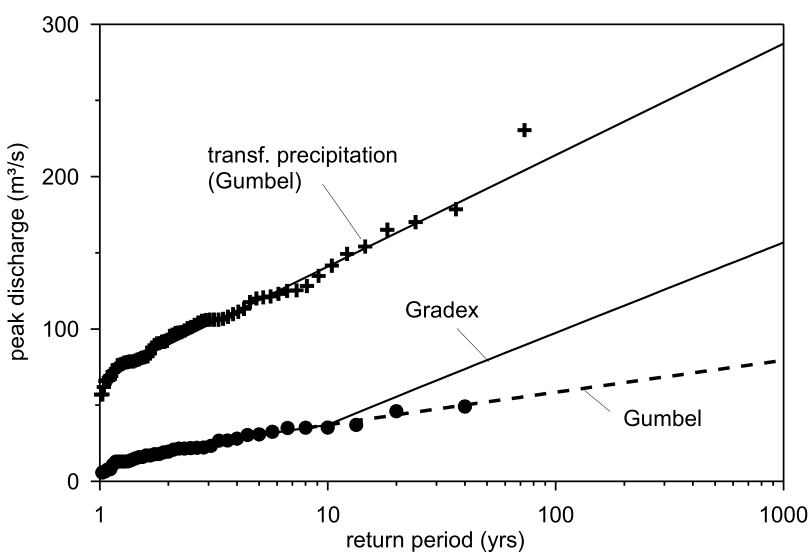

Figure 8. Gradex method for the Trisanna at Galtür (97 km^2 catchment area). Transformed precipitation data of the station Partennen are shown as plusses.

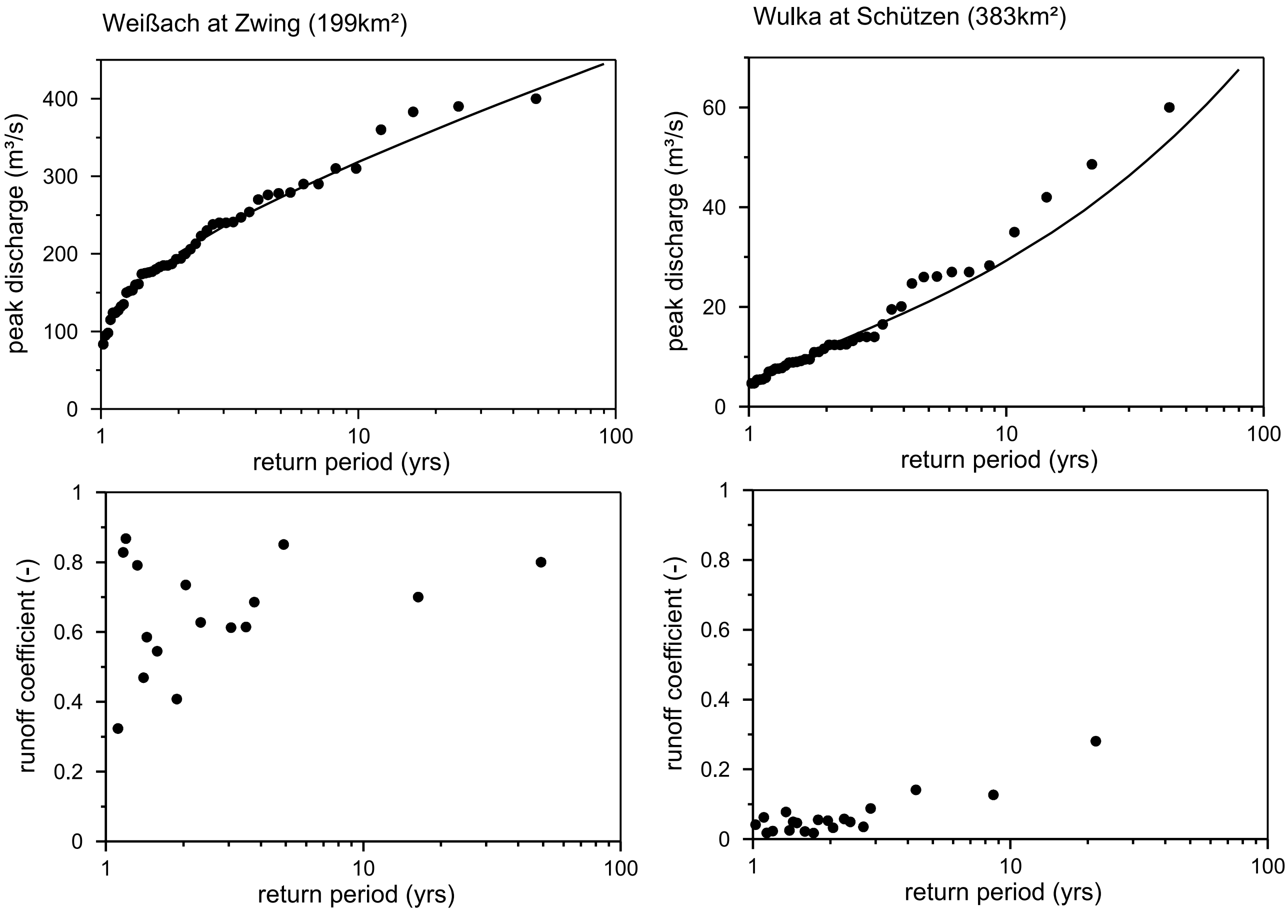

Figure 9. (top) Flood frequency plots and (bottom) runoff coefficients of the associated flood events for (left) Weißach at Zwing (199 km^2 catchment area) and (right) Wulka at Schützen (383 km^2 catchment area).

expect a major increase in the runoff coefficients as they are already close to unity. The flood frequency curve of the catchment in fact shows a downward curvature and, on the basis of the analysis of the runoff coefficients, one would expect that the trend continues, assuming the rainfall regime remains similar. The second example, the Wulka at Schützen, is located in the flat eastern part of Austria close to the Hungarian border and is one of the driest areas in Austria with mean annual precipitation of about 600 mm. At the Wulka, the runoff coefficients are much lower. For the smallest floods, the runoff coefficients are less than 0.05 and they very significantly increase with increasing return periods. The runoff coefficient of the largest flood is 0.3. As rainfall becomes more extreme one would well expect that the runoff coefficients increase to 0.5 and more. The flood frequency curve of the catchment shows an upward curvature and, on the basis of the analysis of the runoff coefficients, one would expect that the trend continues, assuming the rainfall regime remains similar. With the causal information on the runoff coefficients available, an analyst would in both cases extrapolate the flood frequency curve much more confidently than without such information. While no formal method is used, the expanded causal information along with hydrological reasoning gives much more credence to the flood estimates.

[29] The above examples have focused on the rainfall-runoff relationship but floods may also be generated by snowmelt, and by different types of rain storms. One would expect that the different flood producing processes imprint in a different way on the flood frequency curve. For example, as the energy available to snowmelt is limited by the solar constant, one would expect flood frequency curves associated with snowmelt induced floods to level off at large return periods. Conversely, flood frequency curves that results from flash floods may increase more steeply with large return periods in a similar fashion as shown in the previous example.

[30] The flood process types of *Merz and Blöschl* [2003] are used here to illustrate the point. They classified floods in Austria into long-rain floods, short-rain floods, flash floods, rain-on-snow floods, and snowmelt floods based on synoptic analyses of a range of relevant data. Long-rain floods are associated with rainfall over several days or possibly weeks, including low-intensity rainfall, which exceeds the storage capacity of the catchments. Short-rain floods are associated with rainfall of short duration and high intensity which saturate parts of the catchment. Flash floods are associated with short, high-intensity rainfalls, mainly of convective origin that occur locally. The main difference between flash floods and short- rain floods is the smaller spatial extent of

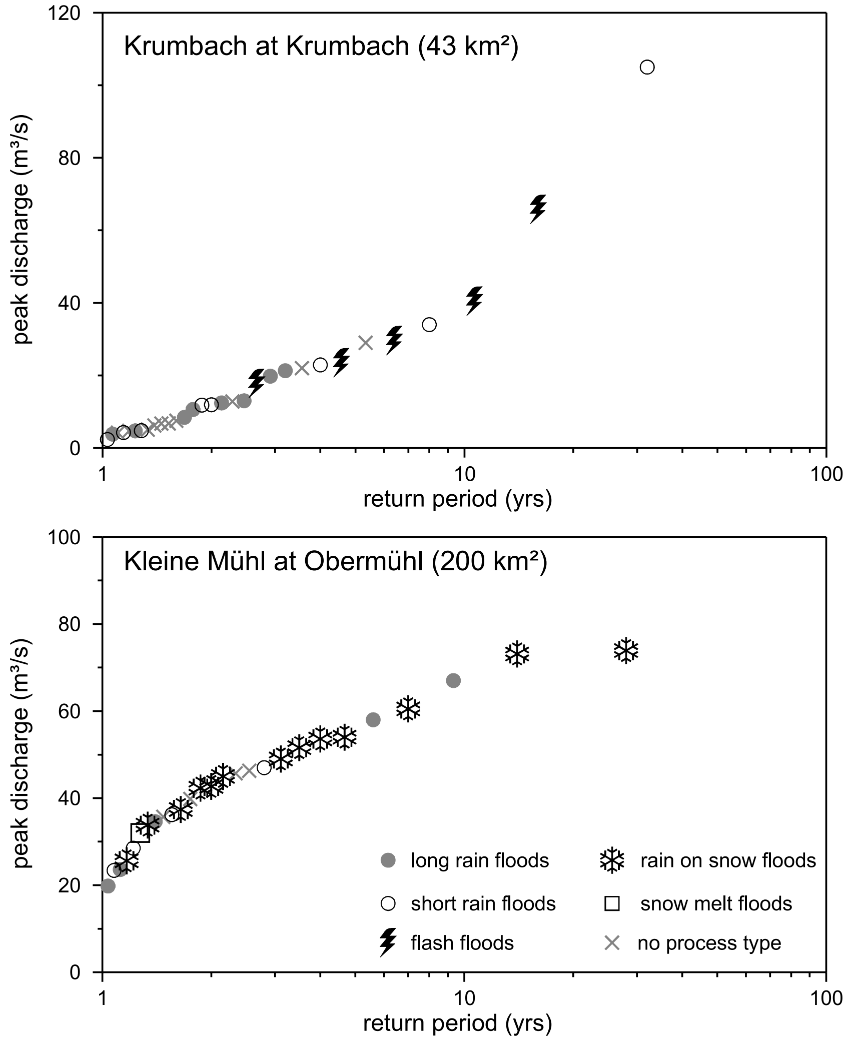

Figure 10. Flood frequency plots with the process types indicated. (top) Krumbach at Krumbach (43 km^2 catchment area). (bottom) Kleine Mühl at Obermühl (200 km^2 catchment area).

the former. Rain-on-snow floods can occur if rain falls on an existing snow cover. Snowmelt floods result from the increase in streamflow during fair weather periods often associated with a rapid increase in air temperature. These types have here been combined with the flood frequency curves. Two examples are shown in Figure 10. The first example is the Krumbach catchment in southeastern Austria. This is a rather warm region with rolling hills. Convective events are known to occur frequently and floods mainly occur in summer when the soils are dry. The types shown in the flood frequency curve (Figure 10) indicate that the small floods are produced by various processes while the largest floods are associated with short-rain floods and flash floods only. This suggests that this type becomes more important as the magnitude of the event increases. The second example is the Kleine Mühl at Obermühl in the North of Austria close to the Czech border. Although the topography is similar, the climate is much cooler with snow depths of up to a meter in winter. Floods tend to occur in winter and early spring when the soil moisture status is high. Rain-on-snow floods occur frequently and they include the largest events (Figure 10). At Krumbach, the smallest floods start at very small values while at the Kleine Mühl the smallest floods start at much larger values. This is because of the much wetter moisture conditions at the Kleine Mühl where floods tend to occur in winter. While the analysis of the flood process types do not directly translate into flood estimates, they provide insight. The types can be used to interpret the shape of the flood frequency curve and the way the flood mechanisms change with the magnitude of the event. In a similar vein, they can be used in regional analyses to interpret homogeneous regions of similar flood producing processes.

[31] The examples above have assumed that local runoff data are available that can be analyzed in various ways. For ungauged catchments, the information is much more limited. Causal information expansion may hence be more indirect. The standard approach in flood frequency analysis is to use catchment attributes, in some way, to infer the flood characteristics from neighboring, gauged catchments. On average this may give adequate flood estimates [see, e.g., *Merz and Blöschl*, 2005] but catchment attributes available at the regional scale, such as soil type or geology, are often poor indicators of hydrologically relevant infor-

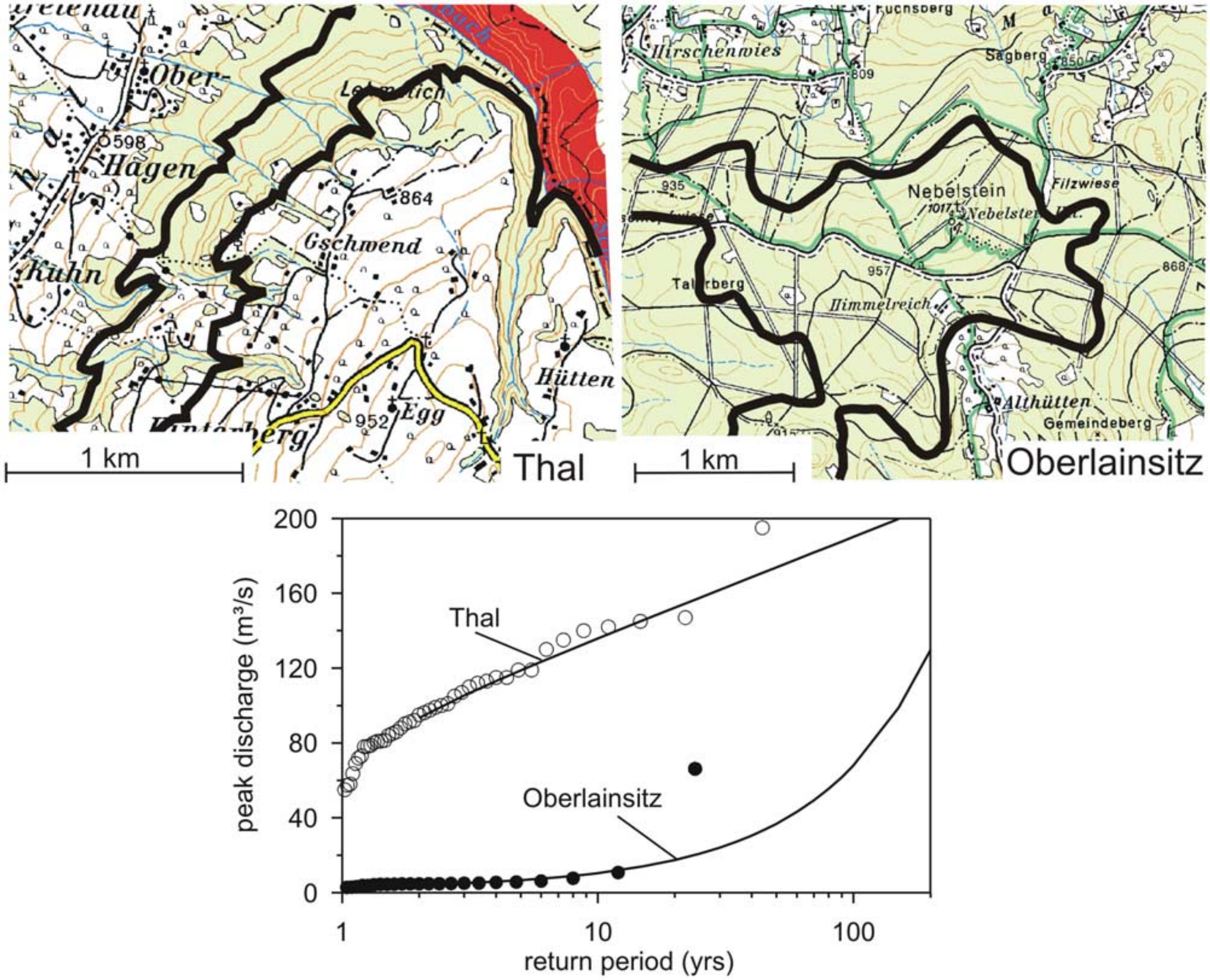

Figure 11. (top) Topographic maps of representative landforms of (left) the Rotach at Thal (90 km^2 catchment area) and (right) the Lainsitz at Oberlainsitz (81 km^2 catchment area) catchments. Two contour lines are marked as thick black lines to demonstrate the degree of incision of the streams. (bottom) Flood frequency plots of observed flood data in the two catchments.

mation, such as preferential subsurface pathways. Alternative or additional process indicators could be used to better constrain the estimates. Local field surveys may provide substantial insight into what are the important processes based on a range of process indicators. One example are indicator plants that have been used by *Markart et al.* [2004] to infer the average moisture conditions of soils and hence runoff coefficients in alpine catchments. Alternative examples are given below.

[32] The first example considers the landform of catchments. In Figure 11, two sections of the topographic maps of Austria at the 1:50000 scale are shown. The left maps shows the Rotach catchment in western Austria, the right map shows the Lainsitz catchment in northern Austria. From a landform perspective, the striking difference between the two maps is the degree of incision of the channels: deeply incised channels in the case of the Rotach catchment as indicated by the breaks in the topographic contour lines and hardly any incision in the case of the Lainsitz catchment as indicated by smooth contour lines. Incised channels are, apparently, a result of erosive forces due to regular large floods, while the smooth landform points to low or moderate floods. Conversely, it is likely that the more incised landform will exacerbate runoff production and routing thereby increasing flood flows in the Rotach catchment. This is hence an example of landform-hydrology feedbacks. This hydrological assessment of flood behavior of the two catchments based on the analysis of channel incision is clearly reflected in the observed flood data. The floods in the Rotach catchment are much larger than those in the Lainsitz (Figure 11, bottom) even though the catchment sizes are similar (90 and 81 km^2, respectively). The mean annual flood (MAF) of the Rotach catchment is about 100 m^3/s while that of the Lainsitz is only 7.6 m^3/s. Also, the shape of the flood frequency curve differs. The Rotach catchment has the characteristics of a wet catchment with frequent large floods; that is, the smallest floods are relatively large and the flood frequency curve continues as a straight line in the semilogarithmic plot. Conversely, the Lainsitz catchment has the characteristics of a dry catchment where most floods are small and large floods are rare; that is, the smallest floods are small and the flood frequency

Table 4. Catchment Attributes of Rotach at Thal and the Lainsitz at Oberlainsitz Catchments

	Rotach at Thal	Lainsitz at Oberlainsitz
Catchment area (km^2)	90	81
Mean topographic elevation (m)	739	835
Mean topographic slope (%)	10	13
Maximum channel length (km)	16	11
Clay, marl, sand and sandstone (%)	100	0
Granite, gneist and schist (%)	0	100
Cambisol (%)	30	0
Luvisol (%)	70	0
Podsol (%)	0	85
Forest (%)	55	76
Grass (%)	45	24
Mean annual precipitation (mm)	1794	834

curve indicates an upward curvature. In the case of the Rotach one would hence confidently extrapolate the observed flood sample as shown while for the Lainsitz one would expect that much larger floods can occur, so the tail of the flood frequency curve should be much steeper. The differences between the two catchments are also reflected by other indicators such as the mean annual precipitation which is 1794 mm and 834 mm for the Rotach and Lainsitz, respectively (Table 4). Mean annual precipitation is an indicator of landform-hydrology feedbacks at the scale of centuries rather than at the event scale. There are also differences in the geology of these two catchments. Rotach consists of clay, marl, sand and sandstone. Owing to the dominance of clay and marl, only a small part of rainfall infiltrates to recharge groundwater. The geology of the Lainsitz catchment is mainly granite and gneiss. Weathering has produced sandy soils with a large infiltration capacity.

[33] The Wienerbruck and Mitterbach catchments of the second example are two adjacent catchments of similar size located in the lower alpine region of Eastern Austria. Figure 12 shows two photographs that are representative of the landforms and the vegetation of the two catchments. In the Mitterbach catchment (Figure 12, top left), the stream channel is mossy and no traces of flood events are visible. This is an obvious indicator of little hydrologic activity, so flood runoff can be assumed to be small. In contrast, the neighboring catchment, Wienerbruck (Figure 12, top right),

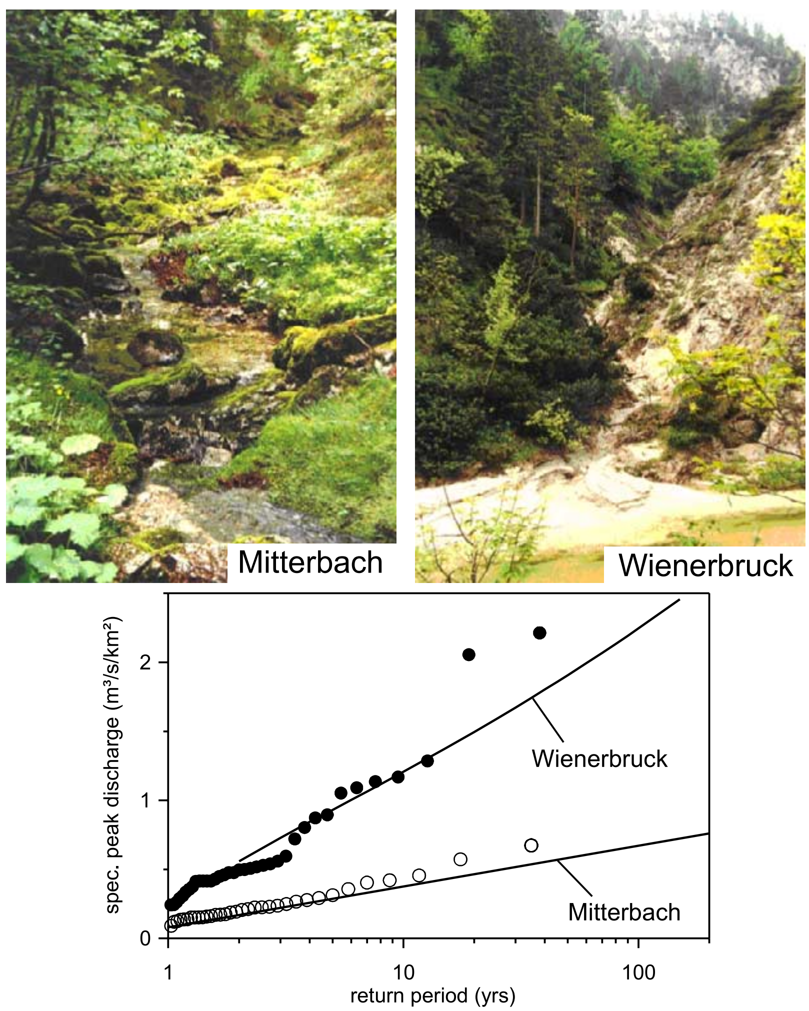

Figure 12. (top) Photographs that are representative of the landforms in (left) the Ötscherbach at Mitterbach (30 km^2 catchment area) and (right) Große Erlauf at Wienerbruck (36 km^2 catchment area) catchments. (bottom) Flood frequency plots of observed flood data in the two catchments.

Table 5. Catchment Attributes of Two Adjacent Catchments in the Austrian Alps

	Ötscherbach at Wienerbruck	Große Erlauf at Mitterbach
Catchment area (km^2)	36	30
Mean topographic elevation (m)	1013	984
Mean topographic slope (%)	30	22
Maximum channel length (km)	10	9
Limestone (%)	20	13
Dolomite (%)	80	87
Rendzina (%)	100	100
Forest (%)	84	81
Grass (%)	14	17
Rock (%)	2	0
Mean annual precipitation (mm)	1680	1415

exhibits signs of erosion rills and deeply incised channels. Clearly these are indicators of high hydrologic activity, particularly during high flow and flood events. Similar as in the previous example, the flood data are consistent with this hydrological assessment (Figure 12, bottom). The Wienerbruck floods are significantly larger than the Mitterbach floods although the difference is smaller than in the Rotach/Lainsitz example. The mean annual floods in Mitterbach and Wienerbruck are 7.2 and 23.7 m^3/s. More importantly, the Wienerbruck flood frequency curve is significantly steeper, so the 100-year flood peaks, as estimated from the sample is about 20.5 and 81.1 m^3/s, respectively. In contrast to the previous example, the differences in the hydrological behavior are not apparent in the catchment attributes as derived from digital data sets. Land use, soil type and dominant geologic formation are similar for the two catchments (Table 5). Wienerbruck is slightly steeper which would suggest somewhat faster response and mean annual precipitation is slightly larger but the differences are small, so regressions to catchment attributes will at best give 30% differences in the 100-year flood while the observed data indicate that the 100-year flood at Wienerbruck is four times that of Mitterbach. It would not be possible to predict the differences in catchment response between the two catchments on the basis of the quantitative catchment attributes and formal methods alone. In contrast, soft information obtained through a visual examination of the catchments during site visits may help tremendously. Clearly, site visits are instrumental in a hydrological assessment.

6. Summary and Conclusions

[34] Although most hydrologists would agree on the importance of hydrological reasoning in flood frequency estimation, most publications in the hydrological literature have focused on subtleties of the estimation problem. In this paper we argue that, in flood frequency analysis, much better use should be made of the wealth of hydrological knowledge gained in the past century. While the flood peak sample is an important source of information there may exist numerous other sources that are hydrologically relevant and these should be used to obtain more accurate estimates. It is hence essential to expand the information beyond the flood sample at the site of interest. We suggest that the expansion of information can be grouped into three types: temporal, spatial and causal expansion. We give examples of the three types of information expansion and illustrate how the information can be used in diagnostic analyses to assist in hydrologically based flood frequency estimation. While formal methods exist to incorporate some of this information, there is a rich diversity of hydrological processes that are relevant to flooding and these are often site specific. In the examples, we illustrate that it is difficult to fully capture the diversity of processes by formal methods. In contrast, hydrological reasoning can be site specific. We show how hydrological reasoning can provide diagnostic findings that give guidance on adjusting quantitative estimates from formal methods to more fully capture the subtleties of the flood characteristics at the site of interest. We believe that this approach gives a more complete representation of flood processes at a given site than the existing formal methods alone and propose the term "flood frequency hydrology," as opposed to flood frequency statistics, to reflect the focus on hydrological processes and hydrological reasoning.

[35] Table 6 summarizes the examples in terms of the relevant processes, data used, the information gained and the more general message for flood frequency hydrology. The examples provided here are a small sample of the variety of processes that may be encountered in different parts of the world. In Austria, additional processes include Karst effects, swamps, dam break floods and debris flows, and in other parts of the world, cyclones, estuarine floods, groundwater driven floods, desert floods and ice jams can be the driving processes. While the hydrological reasoning will depend on the relevant processes, the basic principle of reasoning based on a maximum of relevant information remains similar. Similarly, the type of data used here are a small fraction of the type of information that may be relevant. In particular, proxy data can be immensely varied yet very useful for obtaining more reliable flood frequency estimates. In contrast, the information gained may appear to be simple in that terms such as "smaller" or "larger" appear in Table 6. While the information can be framed in more quantitative terms, the emphasis, here, is on the main effects that may not be captured by seemingly rigorous formal methods based on limited information. The message from the examples is similar: Information expansion, in terms of time, space and causality can be extremely useful although care must be taken. The Zemmbach and St. Aegyd examples illustrate that there may exist trade-offs between the merits of temporal/spatial information expansion and possible trends/heterogeneity in flood behavior that need to be assessed by hydrological judgment. Also, while we have classified the information expansion into spatial, temporal and causal, they are often used in combination. For example, in the St. Aegyd catchment, spatial information (from neighboring catchments) was used along with an interpretation of the shape of the hydrograph to identify subsurface processes which is clearly causal information. The focus of this paper has been on demonstrating the richness of processes and the value of spatial, temporal and causal information expansion. Some of the analyses in the paper are already part of the background of applied hydrologists, although too little attention has been given to them in the scientific literature. In a companion paper [*Merz and Blöschl*, 2008] we show, again by example, how the different sources of information can be combined by hy-

Table 6. Summary of the Examples to Illustrate the Information Expansion and Hydrological Reasoning[a]

Example: Stream/Location	IE	Figure	Processes	Data	Information Gained	Message
Klambach/Sturmmühle	T	1	Climate fluctuations, clustering	Long flood records in neighboring catchment	Floods in observation window are small relative to long-term trend, outlier is not exceptional	Temporal IE allows for more accurate flood estimates over planning horizon
Drau/Villach	T	2	Climate fluctuations, clustering	Historical photos	Return period of recent floods is larger than suggested by flood sample	Similar as above but longer period and proxy data instead
Zemmbach/Sausteinaste	T	3	Human impact (reservoir)	Flood data series	Dam construction has reduced floods	Value of temporal IE depends on whether past is representative of future (trends)
Altenmarkt/Enns	S	4, 5	Bypass of stream gauge	Regional flood data, inundation maps	Data problems (distribution truncated)	Spatial IE is useful; different types of information to corroborate findings
Unrechttraisen/St. Aegyd/	S	6	Subsurface flow in gravel deposits	Hydrograph shapes in regional context	Smaller floods than regional trend confirmed	Subtleties may not be captured by formal methods, hydrological interpretation needed
Teischnitzbach/Spöttling	S	7	Storm tracks, topographic shading	Topographic configuration, regional flood timing	Smaller floods than regional trend confirmed	Similar as above but for another process
Trisanna/Galtür	C	8	Precipitation, climate fluctuations	Long precipitation records	Extreme floods are larger than indicated by flood sample	Causal IE allows for more accurate extrapolation to large return periods
Weißach/Zwing Wulka/Schützen	C	9	Runoff generation changing with magnitude of event	Runoff coefficients for events of different magnitudes	Extreme floods are smaller/larger than indicated by flood sample	Same as above but for case where runoff coefficient explains much of the shape of the flood frequency curve
Krumbach/Krumbach Kleine Mühl/Obermühl	C	10	Synoptic, convective events; floods due to snowmelt, rain-on-snow	Flood types	Change in process with return period	Understanding of processes may assist in more accurate extrapolation and regionalization
Rotach/Thal Lainsitz/Oberlainsitz	C	11	Landform-hydrology feedbacks	Landform from maps	Floods are smaller/larger than regional trend	Process indicators (proxy data) can be used to estimate floods in ungauged catchments; regression works well with MAP as a surrogate
Mitterbach/Mitterbach Ötscherbach/Wienerbruck	C	12	Landform-hydrology feedbacks, weathering	Landform, vegetation, hydrological activity from field trip	Floods are smaller/larger than regional trend	Same as above but regression does not work well (more subtle processes)

[a]T, S, C stands for temporal, spatial, and causal information expansion (IE). MAP is mean annual precipitation.

drological reasoning to obtain more informed estimates of flood frequency than is possible by formal methods alone.

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