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Proposed Swedish Spillway Design Floods in Relation to Observations and Frequency Analysis

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Proposed guidelines for the computation of spillway design floods in Sweden are described. The guidelines are based on the transformation of extreme hydrological conditions to floods by use of conceptual hydrological models.

Floods computed according to the guidelines are compared to observations for both autumn conditions when rainfall dominates and for snowmelt conditions in spring. The highest floods are in the order of 60 % of the proposed guidelines.

Comparisons with frequency analysis show that the computed floods are well beyond the 10,000 year flood according to the Gumbel and Lognormal 2 distribution functions, while the results according to Lognormal 3 are more uncertain.

Introduction

Safe rules for the computation of spillway design floods are a major concern in many countries. Several dam incidents and failures have clearly revealed a tendency to underestimate the hydrological extremes. Therefore responsible authorities in many countries have been forced to reevaluate their design flood practices, and a large number of dams have been redesigned. The problem was given extra attention at the 16th International Congress on Large Dams (ICOLD 1988).

A flood in 1983 in the upper River Indalsälven was the starting point for a new interest in spillway design criteria and practice in Sweden. A committee, established jointly by the Swedish Meteorological and Hydrological Institute and the hydroelectric power industry, was given the mandate to propose new guidelines for spillway design floods, and several research projects were started for better understanding of the mechanisms behind extreme floods and associated risks. In January 1989 the committee delivered its report (The Swedish Committee on Spillway Design 1989), which is presently (spring 1989) undergoing review by concerned organizations. The guidelines take advantage of modern hydrological modelling techniques and are to a great extent influenced by international practice, although some components are specific for the climatological and hydrological conditions in Sweden.

In the following presentation, the proposed guidelines for computation of design floods are briefly presented. Comparisons with observed extreme floods are shown together with attempts to assess the order of magnitude of the probabilities of the design floods. In spite of all uncertainties concerning extrapolation of frequency distribution functions to low probabilities it is concluded that the proposed floods generally have an annual probability of exceedance, which is less than 1/10,000, *i.e.* the design flood exceeds the 10,000 year flood.

Short Description of the Proposed Guidelines

The Swedish Committee on Spillway Design has considered two fundamentally different approaches to the problem of spillway design; frequency analysis of observed floods and hydrological modelling. Although frequency analysis is attractive, as it gives a specified return period, its use entails a large amount of uncertainty. Firstly, the choice of distribution function opens a great span, within which the extreme flow may occur. Secondly, each one of the distribution functions has confidence limits, which widen dramatically when low probabilities are approached.

The use of hydrological models, on the other hand, gives the possibility to combine hydrologically rare events, such as extreme rainfall, low soil moisture deficit and intense snowmelt. The result is an extreme but not physically impossible flood.

The method has the advantage that not only the peak flow but also the whole hydrograph is obtained. This is necessary information for any routing of flow through a reservoir. The main drawback of the use of hydrological models is that it is difficult to assess the probability of the flood.

The Swedish Committee on Spillway Design, as for example the federal authorities in the USA (NRC 1985) and corresponding organizations in many countries, is in favour of the method based on hydrological models. In contrast to usual practice, the emphasis is not put on precipitation maximization alone, but more on the integrated effect of all hydrologically significant factors. This means that an extreme combination of hydrological factors is sought, without extrapolation of anyone of them out of the range previously observed. It is the belief of the committee that this combination will result in an acceptably low risk.

The proposed guidelines are described by the Swedish Committee on Spillway Design (1989). In this presentation it is only possible to give an outline of the guidelines. The reader is referred to the climatological study of extreme precipitation by Vedin and Eriksson (1988) and the two hydrological studies by Brandt, Bergström, Lindström and Gardelin (1987) and Lindström (1987) for further details.

The Hydrological Models

Floods in Sweden are dominated by snowmelt in spring and rain in autumn. Therefore, separate design flood calculations for these two seasons are suggested. The dams have to be able to meet both these flood situations without failure. Most of Sweden experiences the highest rainfall intensities in summer, but the hydrological significance of these is small, due to a large soil moisture deficit (see *e.g.* Brandt *et al.* 1987).

The separation of the design flood computation rules into two seasons makes it possible to use different hydrological models. In autumn no evapotranspiration or soil moisture deficit is assumed, and the snowmelt contribution is small compared to rainfall. It is therefore sufficient with a model without soil moisture accounting or snowmelt routines. The spring situation is more complex. The areal snow ablation is followed by increasing evapotranspiration and the build-up of a soil moisture deficit. This makes the timing of extreme rain and snowmelt crucial and a full hydrological model is thus required.

The reservoirs of the hydropower system are assumed to be full in autumn, while they are nearly empty before the onset of snowmelt in spring. The latter situation requires that a strategy for the operation of the reservoirs during snowmelt is modelled.

The Swedish Committee on Spillway Design suggests the use of the HBV runoff model (Bergström 1976) for spring conditions and a simplification of the same model (Andersen, Hjukse, Roald and Sælthun 1983) for autumn floods. Other hydrological models with comparable performance (see for example WMO 1986) can, of course, also be used.

The chosen model is first calibrated against observed data. For the simplified version a few rainflood events are normally sufficient, while the full hydrological model requires several years of continuous (normally daily) climatological and hydrological observations.

The calibrated model is finally the basis for the simulation of the design floods. In a complex river system (Fig. 1) with several reservoirs, the flood has to be

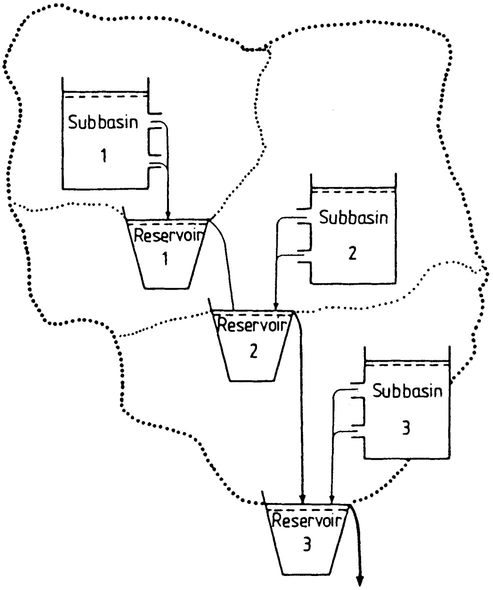

Fig. 1. Schematic picture of a river system when analyzing spillway capacities.

routed through each reservoir, and the outflow is then added to the local inflow down to the next reservoir. This situation is normally the case in Sweden, which makes it preferable to analyse all dams in a river system simultaneously.

Design Precipitation Sequence

Common for all flood simulations is one basic sequence of precipitation over 14 days (Table 1). This sequence is the result of an analysis of all precipitation observations in Sweden over the last 108 years (Vedin and Eriksson 1988) and the studies by Brandt *et al.* (1987) and Lindström (1987). Its return period is difficult to assess, but according to Vedin and Eriksson it should be in the order of magnitude of 10,000 years for 24-hour precipitation over 1,000 km^2. The joint probability for the whole sequence is even smaller because of the assumed coincidence between extreme 24-hour precipitation and extreme 14-day precipitation. The sequence is corrected for geographical region (Fig. 2), catchment area (Fig. 3) and elevation above a given reference level (Table 2). The differentiation of elevation correction

Table 1 – The basic 14-day sequence of precipitation used for the design flood computations.

Day No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Precip. (mm/day)	6	6	6	6	6	10	10	40	120	25	10	10	6	6

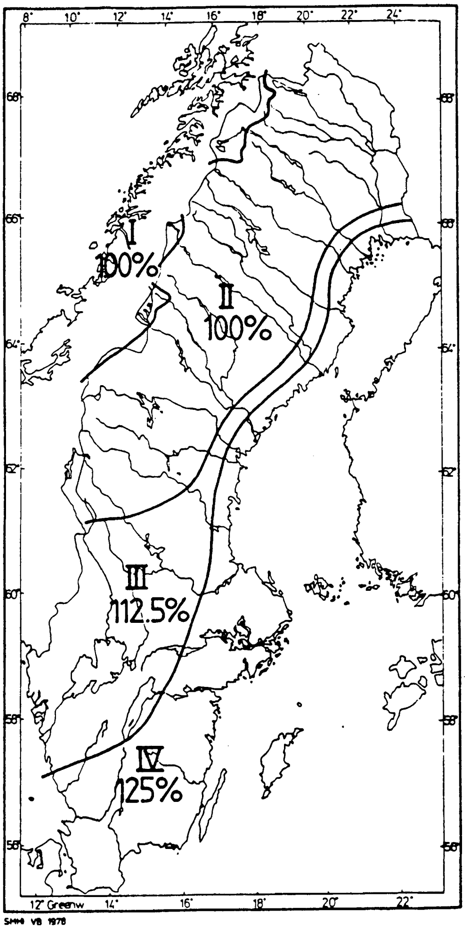

Fig. 2. Suggested regional correction of the basic precipitation sequence used for spillway design floods in Sweden.

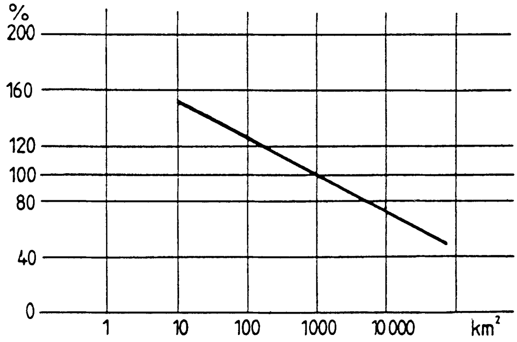

Fig. 3. Suggested areal correction of the basic precipitation sequence used for spillway design floods in Sweden.

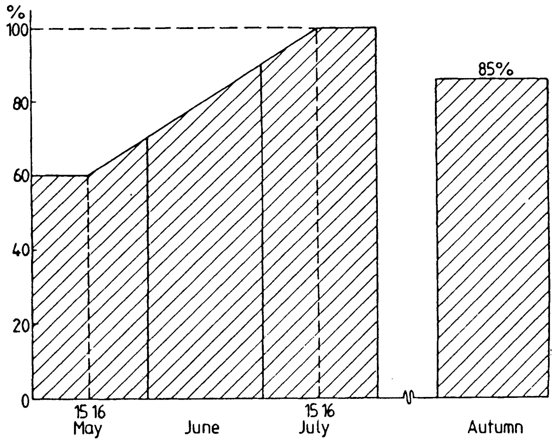

Fig. 4. Suggested seasonal correction of the basic precipitation sequence used for spillway design floods in Sweden.

Table 2 – Elevation correction and reference level for the basic precipitation sequence (from north to south).

River Torneälven to River Indalsälven	17 % per 100 m above 500 m a s l
River Ljungan	15 % per 100 m above 600 m a s l
River Ljusnan and River Dalälven	10 % per 100 m above 600 m a s l
River Klarälven	10 % per 100 m above 700 m a s l
South of Klarälven	no altitude correction

between river basins is motivated by different proximity to the Norwegian coastline.

The basic precipitation is finally corrected for season according to Fig. 4, which is in accordance with observations by Vedin and Eriksson (1988) and other climatological studies. This correction is applied to all regions except for the westernmost parts of the mountains (Region I in Fig. 2), where no autumn reduction can be justified.

Flood Simulation for Autumn Conditions

The design flood simulation for autumn conditions starts with the assumptions that the reservoir is full, that there is no soil moisture deficit or evapotranspiration, and that the initial flow in the river is at an average high level for the season. The spillways are assumed to operate normally, but no water is conveyed by the turbines.

To the design precipitation sequence, properly corrected for region, catchment area, elevation, and season, a snowmelt contribution according to Table 3 is added.

Table 3 – Snowmelt contribution for the design flood simulation. Autumn conditions.

Day No.	...6	7	8	9	10	11	12.....
Snowmelt (mm/day)							
region I	...0	4	6	20	6	4	0.....
region II-IV	...0	2	3	10	3	2	0.....

The volume of this snowmelt has an annual exceedance probability in the order of 1/10 for autumns (Brandt *et al.* 1987). Its timing is chosen to coincide with the most intense rainfall of the sequence.

The combined rainfall-snowmelt sequences is entered into the simplified hydrological model, the design flood is computed and the performance of the reservoir system is analysed.

Flood Simulation for Spring Conditions

The design spring flood simulation starts with reservoirs that are assumed to be emptied to a level, which is normal when a high springflood is expected. No soil moisture deficit is assumed, but evapotranspiration starts, as soon as the snowpack is gone. The initial snowpack is assumed to be of a magnitude of once in 30 years and is obtained from frequency analysis of a long model simulation.

The reservoirs are operated according to normal strategies for years with heavy snowpack. When the reservoir is full, no water is passed through the turbines, but the spillways are assumed to operate normally.

At least ten different snowmelt seasons are computed by the full hydrological model. For each one of these years a 14-day period of observed precipitation is replaced by the design precipitation sequence in a position that is the most critical one for the system of dams. This position is found by trial and error, which means that a large number of model simulations is needed. To avoid unreasonable combinations of high air temperatures and intense rainfall, the temperature observations are lowered by 3° C on the day of maximum precipitation and during the remaining sequence.

As an example, the most critical inflow hydrograph for each one of ten melt periods is shown in Fig. 5 for Sweden's highest dam, Trängslet, in River Dalälven. The corresponding reservoir response is shown in Fig. 6.

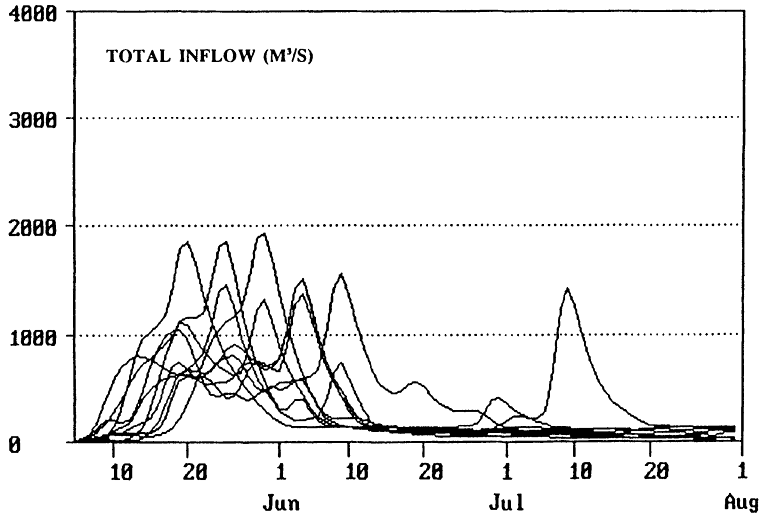

Fig. 5. Examples of critical inflow hydrographs, one for each analysed melt period, for the Trängslet reservoir.

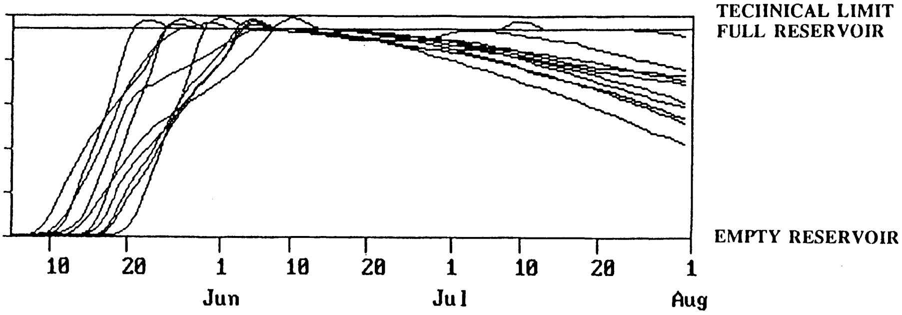

Fig. 6. Examples of reservoir response to extreme inflow and operation strategy for the Trängslet dam.

Comparison with Observed Floods

The verification of guidelines of this kind is difficult and can only give indications of how realistic the values are. A comprehensive discussion on this problem was given by the U.S. Dept. of Commerce (1986) stating that it is not within the state of the art to calculate the probability of *PMF*-scale floods within definable confidence or error bounds.

One of the main difficulties is to assess the joint probability of the climatological and hydrological factors creating extreme floods. Even if the probability distribution of each one of them would be known, which is normally not the case, the probabilities show complex interactions, which hinder estimation of the total risk. One further complication is the spatial and temporal variation in relative importance of each factor.

The Swedish Committe on Spillway Design has chosen a relatively simple comparative study of observed peakflows in an attempt to estimate the probabilities of the proposed design floods. This means that the modelled flows are directly compared to observed peak flows and frequency analysis of observed flows, and that no attempt is made to find the joint probability of the input variables. A similar study for the USA has been shown by Bullard (1986).

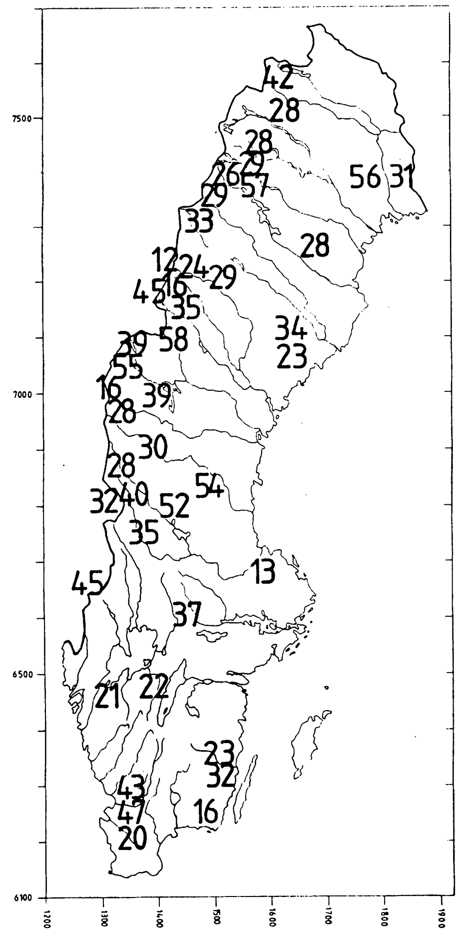

Fig. 7. Ratio between observed floods and computations according to the proposed guidelines (in per cent). Autumn conditions.

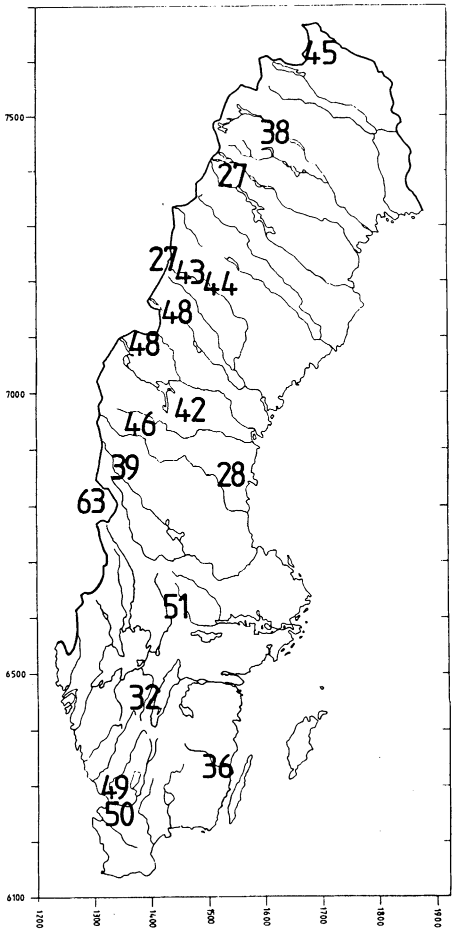

Fig. 8. Ratio between observed floods and computations according to the proposed guidelines (in per cent). Spring conditions.

Results

Design floods were computed according to the proposed guidelines and compared to the highest floods for autumn and spring conditions (Figs. 7 and 8). For autumn 43 basins and 2,156 station-years were used, while the corresponding figures for spring were 18 and 861 respectively. The month and year when the highest floods occurred are given in Table 4.

A major part of the data were subject to frequency analysis according to the Gumbel, Lognormal 2 and Lognormal 3 distribution functions. In Figs. 9 and 10 results expressed as the ratio between the 10,000 years flood and the proposed design flood (in %) are shown for the three distribution functions. According to the Gumbel distribution function the design flood represents a return period longer than 10,000 years (ratio less than 100 %) in all basins, while there are several cases, where the ratio is greater than one, which means shorter return periods for the other two distribution functions.

Discussion

Conclusions from the comparison between design floods and observations have to be drawn with great care. The method is essentially a station-year approach, which means that the problem of independence and regional homogeneity has to be considered. Some dependence, although not dramatic, is shown in Table 4, as some of the peaks have their origin in the same weather system or occur during the same spring. The homogeneity problem is, to some extent, overcome by regionalization of the proposed guidelines.

The above analysis shows that we have reached 58 % of the suggested design flood in the 2,156 analyzed years of record for autumn conditions. Corresponding figures for the snowmelt season are 63 % and 861 station-years. This gives us an indication of the annual exceedance probability of the suggested floods.

When it comes to frequency analysis, we must bear in mind that each analysis is based on relatively short records, and thus the extrapolation is dramatic. The Gumbel and Lognormal 2 distributions indicate return periods well beyond 10,000 years in most cases, while Lognormal 3 indicates shorter periods in several cases. As an average it seems safe to conclude that the return periods of the suggested design floods are beyond 10,000 years. The discrepancy between probability distribution functions is a good example of the difficulties when interpreting frequency analysis based on short records.

One important conclusion is that no great regional inconsistency is revealed by the comparisons with observed floods except for autumn floods in the southeast of the country, where very low ratios between observations and design floods are shown. This indicates that the suggested climatological differences between regions

Table 4a - Date of occurrence of the highest observed floods. Autumn conditions.

Date year and month	Station	Record	% of Design flood
1902-09	Transtrand	1902-39	40
1912-08	Särna	1909-62	28
1915-07	Hotagen	1911-23 1937-86	58
1920-08	Stenudden	1916-87	57
1925-07	Solberg	1911-87	33
1927-10	Björna	1927-82	23
1928-11	Nättraby	1911-53 1956-76	16
1928- 11	Blankaström	1928-88	23
1928-11	Getebro	1920-75	32
1936-07	Litnok	1931-45	28
1938-09	Storsjön	1916-63	28
1940-08	Handöl	1916-54	16
1943-02	Slumpån	1933-49 1955-75	21
1944-12	Hammarby	1910-88	37
1946-10	Niemisel	1938-86	56
1947-10	Torrön	1914-34 1940-86	37
1947-10	Rutsälven	1939-86	55
1949-10	Ankarvattnet	1945-67 1973-88	45
1954-08	Fjällåsen	1917-67	28
1954-08	Kukkasjärvi	1923-69 1986-88	31
1954-08	Kåtaselet	1948-75	28
1955-12	Simlången	1928-88	43
1955-12	Gårdsilt (part of Simlången)	1944-81	47
1957-09	Höljes	1909-88	32
1959-10	Pahtajaure	1934-69	42
1960-08*	Rebnisjaure	1937-86	26
1960-08*	Fotingen	1916-64	39
1961-08	Näs	1925-70	13
1961-11	Byälven	1911-85	45
1966-07	Sädvajaure	1902-41 1947-86	29
1967-10	Moholm	1929-87	22
1975-09	Ransaren	1962-87	12

cont.

Table 4a –cont.

1979-07	Kultsjön	1967-87	24
1979-07	Malgomaj	1964-87	29
1979-07	Borgasjön	1932-87	16
1980-12	Klippan	1909-87	20
1985-09	Vässinkoski	1970-88	52
1985-09	Stadarforsen	1958-88	35
1985-09	Sveg	1914-61 1963-88	30
1985-09	Alfta	1914 -25 1940-88	54
1987-08	Torrböle	1949-87	34
1987-08	Storsjouten	1946-87	35
1987-08	Parki	1971-87	29

Table 4b – Date of occurrence of the highest observed floods. Spring conditions.

Date year and month	Station	Record	% of Design flood
1916-05	Torrön	1914-34 1940-88	48
1922-06	Sädvajaure	1902-41 1947-86	27
1945-05	Moholm	1929-87	32
1951-04	Simlången	1929-88	49
1951-04	Blankaström	1929-88	36
1966-05	Trängslet	1963-88	39
1966-05	Sveg	1962-88	46
1967-04	Hassela	1919-88	28
1967-05	Kultsjön	1954-87	43
1967-05	Höljes	1909-88	63
1968-06	Lannavaara	1923-27 1959-87	45
1970-04	Gårdsilt	1944-81	55
1973-06	Storsjouten	1946-67 1973-87	48
1977-05	Torpshammar	1969-88	42
1977-05	Hammarby	1910-88	51
1980-06	Ransaren	1954-87	27
1986-05	Malgomaj	1954-87	44
1987-06	Parki	1972-88	38

* One week apart

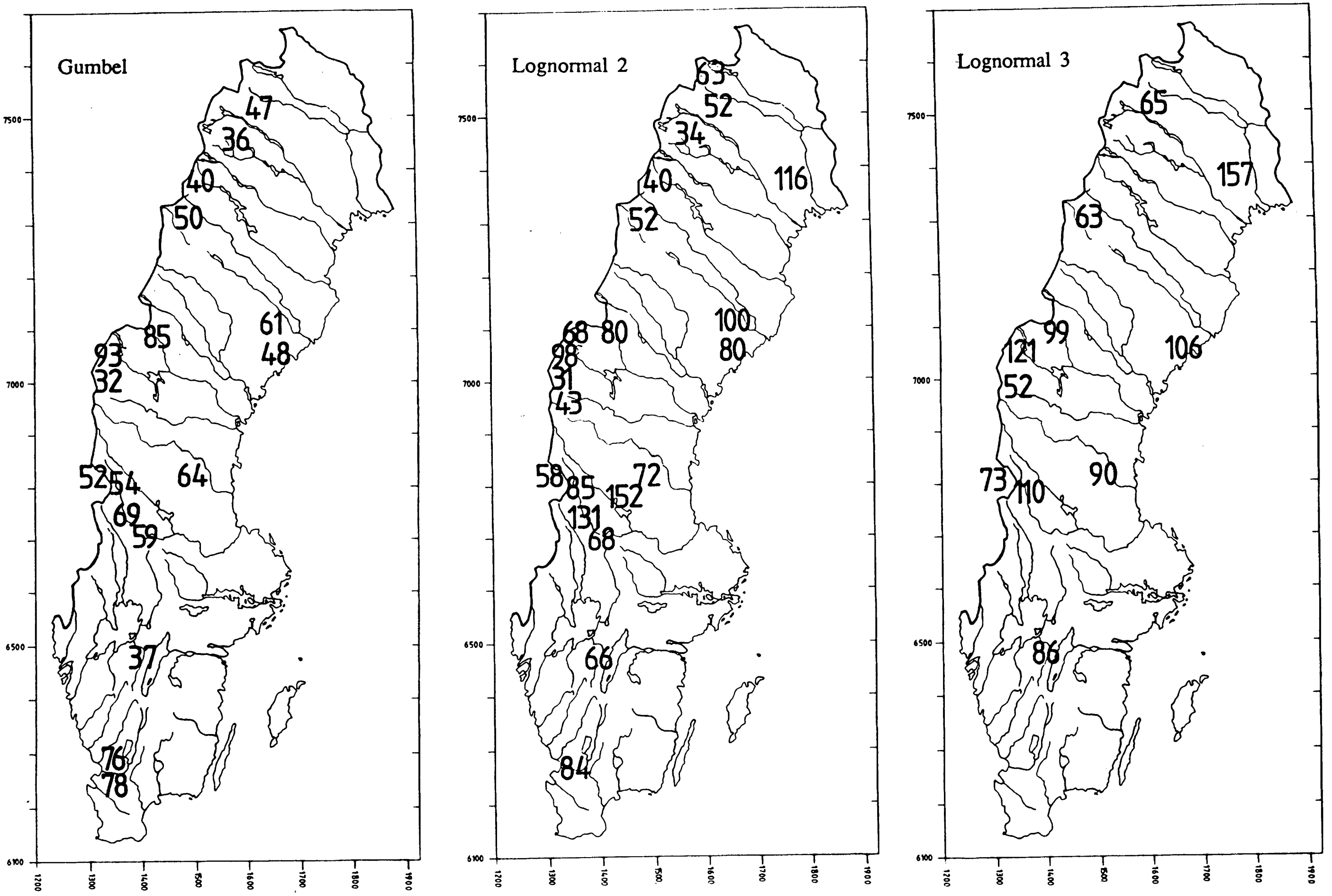

Fig. 9. Ratio between 10,000 years floods according to three distribution functions and flood according to the proposed guidelines (in per cent). Autumn conditions.

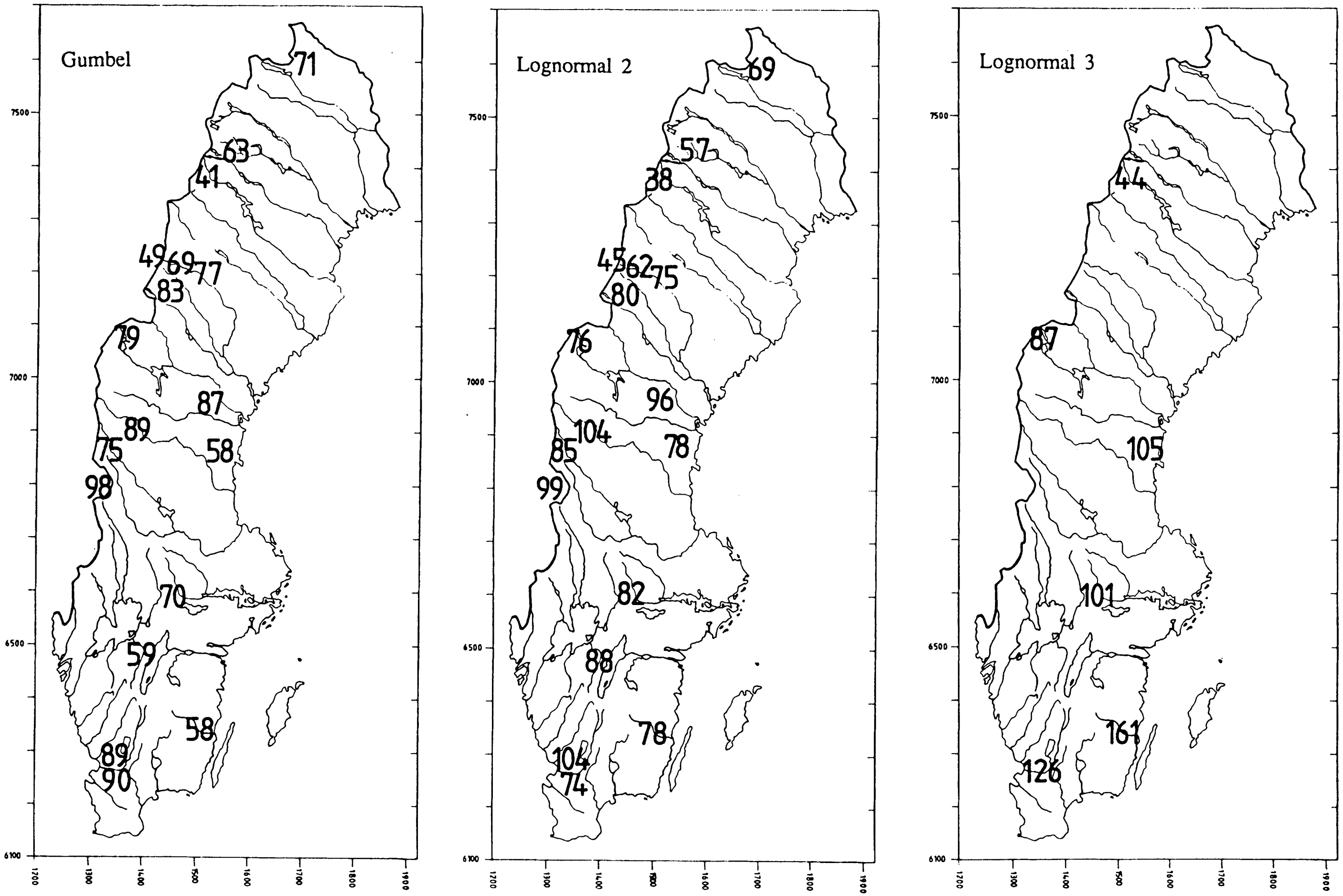

Fig. 10. Ratio between 10,000 years floods according to three distribution functions and flood according to the proposed guidelines (in per cent). Spring conditions.

are reasonable for most parts of Sweden but that an amendment may be needed for autumn conditions in the southeast. There are also indications that floods are overestimated at high elevations. Therefore the elevation corrections according to Table 2 are still subject to studies.

The observed peaks during spring are closer to the proposed design floods than are autumn floods. This difference can be accepted in light of the greater variability in autumn floods, which are often caused by single rainfall events.

One uncertainty, which is not addressed in this study, is the performance of the model used for calculation of the design flood. Regardless of the choice of hydrological model, there are parameters which have to be found by calibration or in other ways. The final choice of model parameters effects the peak flow, and a sensitivity analysis is therefore justified. The uncertainty is further emphasized by the extrapolation of the model beyond its range of calibration.

Floods of the order of magnitude suggested by the proposed guidelines are difficult to comprehend. They have not been experienced during the relatively short time span of operation of a fully developed hydroelectric power system. It is, however, interesting to note that each hydrological factor is assumed to be extreme but not maximized. This means that they have all occurred or nearly occurred. What makes the design floods so large and the probability so low is the assumption of critical timing of all these factors. This is particularly true for the snowmelt season, when the critical rainfall sequence is assumed to occur during a few critical weeks.

The ratios presented in Figs. 8 and 10 refer to a system without reservoirs. When the guidelines are applied to real systems of reservoirs, the timing of the filling of the reservoir will be another factor, which further surpresses the risks.

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