Nordic Hydrology, 24, 1993, 1-12

Frequency of Extremes and its Relation to Climate Fluctuations

I. Krasovskaia
Hydroconsult AB, Höganäs, Sweden

L. Gottschalk
University of Oslo, Norway

Possible consequences of climate change concern both changes in long-term mean values of runoff and changes in frequency and magnitude of extreme runoff events. The physical safety of dams and protection against floods are not sensitive to the moderate changes in mean values but to the frequency and magnitude of extremes. This study presents the results of the analyses of the changes in the behavior of the extreme runoff values due to observed changes of temperature and precipitation. Statistical parameters of the magnitude of floods as well as their intensity have been studied. An attempt is also made to establish regional probability distribution curves for the frequencies of the extreme floods for different patterns of changes in the climatic variables considered.

Introduction

An analysis of the stability of flow regimes (Krasovskaia and Gottschalk 1992) has shown that rather moderate fluctuations in the mean annual temperature and precipitation cause changes in flow regime patterns, *i.e.* the timing and magnitude of the average high and low flows. These noted changes of average patterns could be expected to be still more pronounced in the behavior of individual extreme events, their intensity, magnitude and probability of occurrence. These latter three characteristics of extreme floods and their sensitivity to the observed increase/decrease in mean annual temperature and precipitation have been investigated for different flow regimes by the example of Norway.

Two independent approaches for the analysis of extremes have been used. The first one is based on partial duration series and the theory of Poisson processes. In this case the intensity and magnitude of extremes over some given threshold level are compared for warm/cold and wet/dry years, respectively. The second one is based on annual flood series and regional frequency curves, which have been compared for warm/cold years.

Data Used

Flow regime regions, which form the background for the present analyses, originate from our previous study of flow regime stability (Krasovskaia and Gottschalk 1992) based on monthly river flow data for a total of 81 gauging stations in the Nordic countries. Most of the basins have an area of less than 2,000 km^2. For the analysis of extremes, daily values from 24 Norwegian stations were used, all 66 years long.

Temperature and precipitation observation series with a common observation period were taken from climatic stations situated in the vicinity of flow gauging stations. A total of 31 temperature and 50 precipitation series for the whole Scandinavia have been used. These series have been split into two sub-series, respectively: one for years with the annual values above the long-term mean and the other for years below. The years corresponding to these respective sub-series are in the following named "warm" and "cold" and "wet" and "dry". For the "warm" years the mean annual temperature was 0.9° C above the long-term mean (the average across all the stations) and for the cold years it was 0.8° C below. For the "wet" years the mean annual precipitation was 122.4 mm higher than the long-term mean and for the "dry" years it was 103.2 mm lower. Runoff series (daily values) have been split accordingly: one sub-series for the "warm" and the other for the "cold" years and then one sub-series for the "wet" and the other for the "dry" years.

Flow Regime Regions

Flow regimes unify underlying processes involved in runoff formation and present seasonal patterns characteristic for certain climatic and physiographic conditions. In the context of possible climate change flow regime classification has the twofold role. One one hand it can be used in the process of validation to check that the correct seasonal patterns are reproduced by climate models. On the other hand, flow regimes, reflecting climate and environment in the basin, indicate the proper choice of hydrologic model formulation.

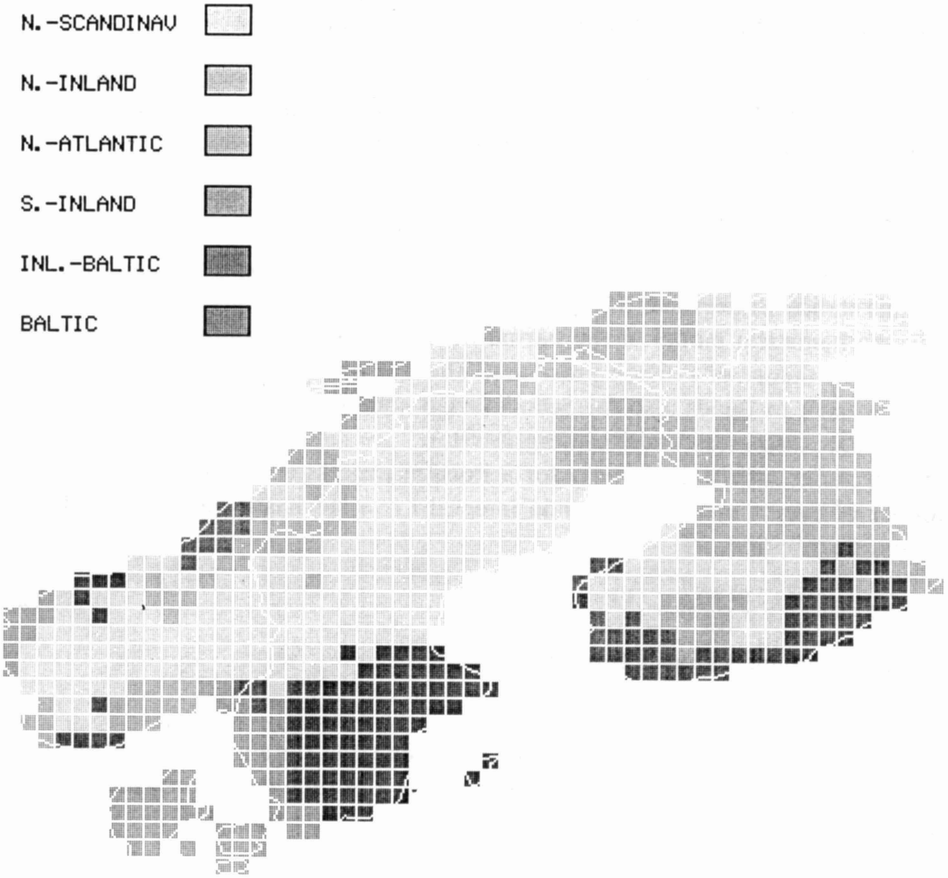

Fig. 1. Flow regime regions.
1 – North-Scandinavian 2 – Northern-Inland 3 – North-Atlantic 4 – Southern-Inland
5 – Inland-Baltic 6 – Baltic

Flow regime classification for the Nordic countries, suggested by Gottschalk *et al.* (1979) and modified and applied for the Nordic countries by Krasovskaia and Gottschalk (1992) has been used. This classification is a quantitative one, based on the time of occurrence of high/low flow, which reflects the role of the genetical sources in flow formation. For the Nordic countries these are snow-melt and rain water. Classification is performed automatically on monthly flow series and the resulting regions are presented on a grid network (0.5°* 0.5°). Six flow regime regions, named after the flow regime types, have been distinguished: North-Scandinavian, Northern-Inland, Southern-Inland, Baltic, North-Atlantic and Inland-Baltic, of which the first five can be found in Norway. Fig. 1 shows the geographical location of the regions.

Changes in the Intensity and Magnitude of Floods

The intensity and magnitude of floods in partial duration series *(PDS)* have been investigated. Dealing with *PDS* we are interested only in the extreme events above a certain chosen threshold. This is calculated from

$$x_0 = m + ks \tag{1}$$

where m is the long-term mean, s the standard deviation and k a frequency factor which has been set equal to 3 in this study. Rosbjerg and Madsen (1992) confirm that this choice ensures that the extracted peaks are true extreme events. A convenient mathematical model of the partial duration series is obtained by using the well-known theory of Poisson processes. There is a large experience of applying this approach to floods also for Scandinavian conditions (see, for example Rosbjerg 1985; Rasmussen and Rosbjerg 1989).

If our series satisfy the criteria for a Poisson process it can be shown that the number of events $n(t)$ within a time interval t is a stochastic variable which has Poisson distribution, *i.e.*

$$P[N(t)=n] = \frac{(\lambda t)^n}{n!} e^{-\lambda t} \tag{2}$$

with the mean and variance given by

$$E[N(t)] \equiv \mathrm{Var}[N(t)] = \lambda t \tag{3}$$

where λ is the average number of events per a time unit (intensity of flood events). We further assume that the extreme flood events X at time i is a stochastic variable which has an exponential distribution function

$$F_X(x) = 1 - \exp\left(-\frac{x}{\alpha}\right) \tag{4}$$

where α is the mean of X. Let $Z(t)$ be the largest exceedance of the threshold x_0 in the time interval $[0,t]$. The process $Z(t)$ can be defined as

$$Z(t) = \sup_{i<t} X_i \tag{5}$$

We can now use the assumption of independence together with Eq. (2) to derive the following expression for the cumulative distribution function for $Z(t)$

$$F_{Z(t)}(z) \equiv P[Z(t)<z] = \exp\{-\lambda t[1-F_X(z)]\} \tag{6}$$

If we set $t=1$ and with X having an exponential distribution (Eq. (3)) we get

$$F_Z(z) = \exp\{-\lambda \exp(-\frac{z}{\alpha})\} = \exp\{-\exp[-\frac{z-\alpha \ln \lambda}{\alpha}]\} \tag{7}$$

where for simplicity we denote $\lambda(1)=\lambda$.

For each of the series of daily runoff values within a flow regime region, the mean value m and the standard deviation s have been calculated and a threshold x_0

Table 1 – Values of λ and α for the different flow regime regions for "warm" and "cold" years in relation to those for the whole period.

Parameters	λ		α	
Years	"warm"	"cold"	"warm"	"cold"
Flow regime region:				
North-Scandinavian	1.118	0.858	1.000	1.020
Northern-Inland	1.115	0.922	1.011	0.989
North-Atlantic	1.208	0.791	0.998	1.006
Southern-Inland*	1.344	0.706	1.009	0.979
Baltic	1.124	0.850	1.032	0.960

* based on limited data

determined in accordance with Eq. (1). The next step has been to establish the *PDS* for each series for their respective thresholds. Finally, these *PDS* were split into two: one for the "warm" years and the other for the "cold" years. Parameters λ and α have been estimated by means of method of moments for the *PDS* for the whole period and for the "warm" years and the "cold" years, respectively. Table 1 shows the results of calculations as averages over flow regime regions, where λ and α are given in the relation to the mean values for the whole series.

It can be seen from the table that the intensity of the floods λ is higher for the series for "warm" years in all the regions. The difference is largest for the North-Atlantic, Southern-Inland and Baltic regions. These results coincide with the conclusions made in our previous study of the stability of flow regimes (Krasovskaia and Gottschalk 1992). As far as the magnitudes of floods are concerned, they remain almost unchanged for the *PDS* for the "warm" and "cold" years. However, taking into account the tendency for the increased intensity of flood events during the "warm" years, the probability of observing floods of large magnitudes do increase.

The estimated values of λ varied between ≈1 and ≈4 and no systematic patterns were found in the fluctuations like, for example, dependence on the catchment area. In order to demonstrate the influence of the flood intensity λ on the magnitude of floods we have calculated hundred-year floods for different λ. Table 2 offers the results of this calculation, with values given in relation to those for the whole series. The largest deviation is naturally observed for North-Atlantic, Southern-Inland and Baltic regions (*cfr* also Table 1). In general, the percentage of deviation seems to reduce with growing λ.

To investigate the influence of the changes in the precipitation on the intensity and magnitude of floods, the analyses have been repeated with a division into "wet" and "dry" years (the series have been obtained in the same way as those for "warm" and "cold" years). Table 3 presents the values of λ and α obtained in relation to those for the whole series.

Table 2 – The influence of the intensity of flood events λ on calculated 100-year floods during "warm" and "cold" years in relation to those for the whole period.

	Deviations					
Years	"warm"	"cold"	"warm"	"cold"	"warm"	"cold"
	λ=1		λ=2		λ=3	
Flow regime region:						
North-Scandinavian	1.073	0.918	1.050	0.950	1.042	0.960
Northern-Inland	1.083	0.936	1.060	0.953	1.057	0.958
North-Atlantic	1.122	0.852	1.083	0.900	1.070	0.916
Southern-Inland*	1.204	0.756	1.143	0.826	1.122	0.849
Baltic	1.111	0.858	1.086	0.890	1.078	0.900

* based on limited data

Table 3 – Values of λ and α for the different flow regime regions for "wet" and "dry" years in relation to those for the whole period.

Parameters	λ		α	
Years	"wet"	"dry"	"wet"	"dry"
Flow regime region:				
North-Scandinavian	1.047	0.909	1.009	0.992
Northern-Inland	1.154	0.782	1.007	0.980
North-Atlantic	1.110	0.811	1.011	0.969
Southern-Inland*	1.450	0.576	1.014	0.955
Baltic	1.180	0.787	1.029	0.963

* based on limited data

The results show that during "wet" years the intensity of floods can increase from about 5% up to 45% compared to the whole period. The decrease during "dry" years seems to be approximately the same. The magnitude of floods is only slightly influenced by the precipitation variation, being around ±1-4%.

Regional Exceedance Probabilities

In a sample of regional data of extremes the probability to observe an extreme value with a return period larger than the number of observation years is much greater than that for the individual series. The probability of exceedance p_i of the largest value for a certain year *i* in a regional sample of independent data was given by Gottschalk (1989)

$$p_i \equiv \frac{1}{Mk+1} + \frac{Mk}{Mk+1}\,\frac{1}{M(k-1)+1} + \dots + \frac{Mk}{Mk+1}\,\frac{M(k-1)}{M(k-1)+1} \cdots$$

$$\cdots \frac{M(k-i+1)}{M(k-i+1)+1}\,\frac{1}{M(k-i)+1} \qquad (8)$$

where M is the number of observation stations in the regional sample and k the number of common observation years (note that in the original paper M and k by mistake has been interchanged). The probabilities p_i can be regarded as the plotting positions for the regional extremes corresponding to Weibull's formula for individual series. As data series are not independent, we have calculated an equivalent number of independent series M_e for each region from the relation (Gottschalk 1989)

$$M_e = \frac{1}{1+(M-1)\rho} \tag{9}$$

where ϱ is the mean regional spatial correlation.

Fig. 2 shows the plotting diagrams for the regional exceedance probabilities calculated for "warm" and "cold" years. The difference in the curves for "warm" and "cold" years is largest for the Baltic region and Southern-Inland region, while for the North-Scandinavian and North-Atlantic regions the difference is very small. For the Northern-Inland region the difference lies somewhere in between. Table 4 illustrates the changes giving the results of calculation of the magnitude of the extreme flood with the return period of 100 years for "warm" and "cold" years in relation to that for the whole period.

It can be seen from the table that, for example, for Baltic region the extreme flood with the exceedance probability 1/100 is more than 15% higher for the "warm" period than that for the whole one, while it is about 11% lower during the "cold" period. The figures in the table demonstrate again that the greatest difference is observed for the southern part of the studied territory (Baltic and Southern-Inland regions). Both of them have previously showed the largest difference between the parameters of the partial duration series. If we compare the deviations from the average for the whole series given in Table 4 to these of α given in Table 2, we can see that the tendency is the same, *i.e.* the largest difference can be observed for Southern-Inland and Baltic regions.

Table 4 – Magnitude of the extreme flood with return period of 100 years for "warm" and "cold" years in relation to that for the whole period.

Years	"warm"	"cold"
Flow regime region:		
North-Scandinavian	1.014	0.988
Northern-Inland	1.017	0.985
North-Atlantic	1.003	0.997
Southern-Inland*	1.111	0.902
Baltic	1.151	0.888

* based on limited data

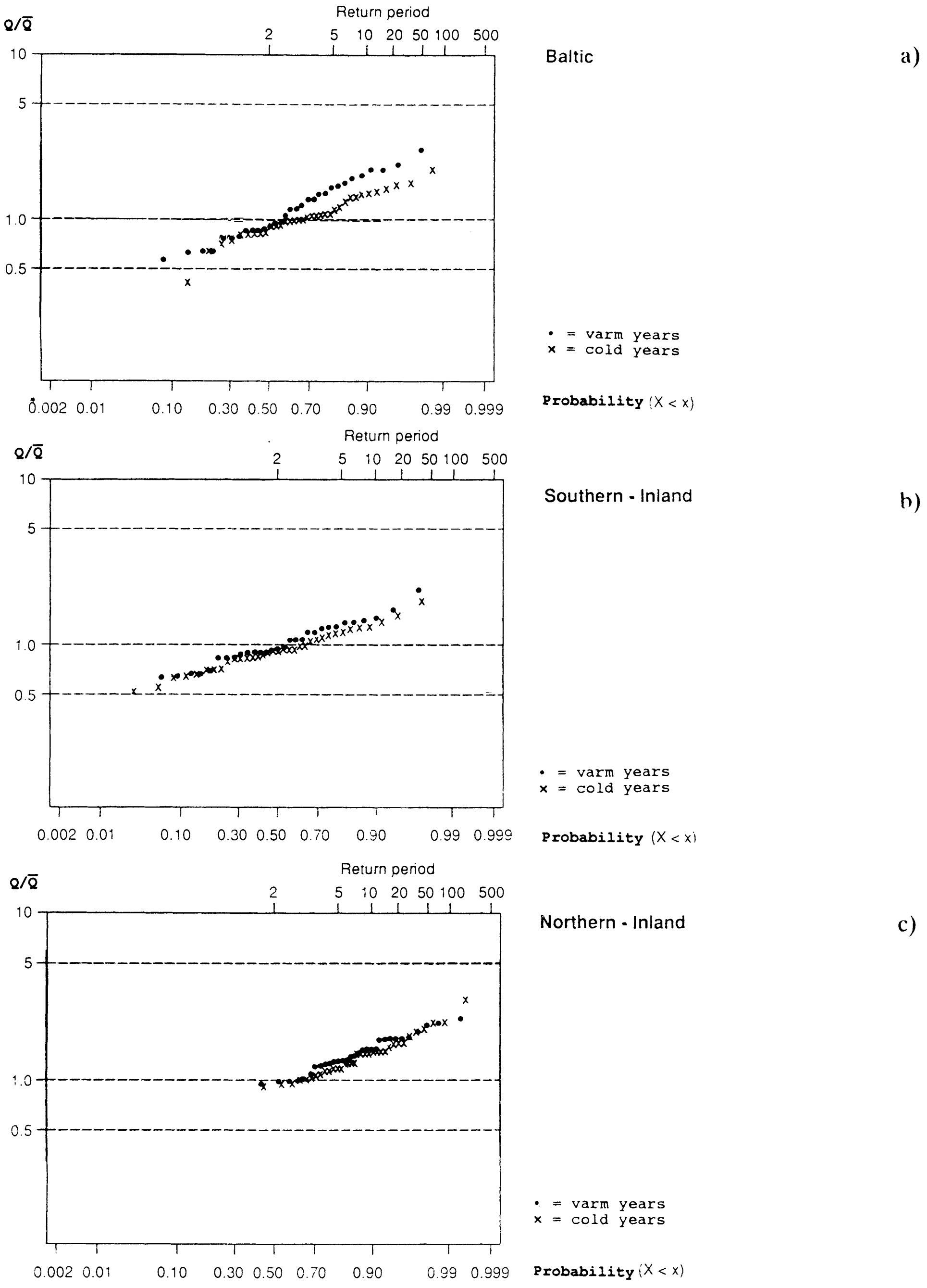

Fig. 2. Regional exceedance probability curves for different flow regime regions, a), b) c), cont.

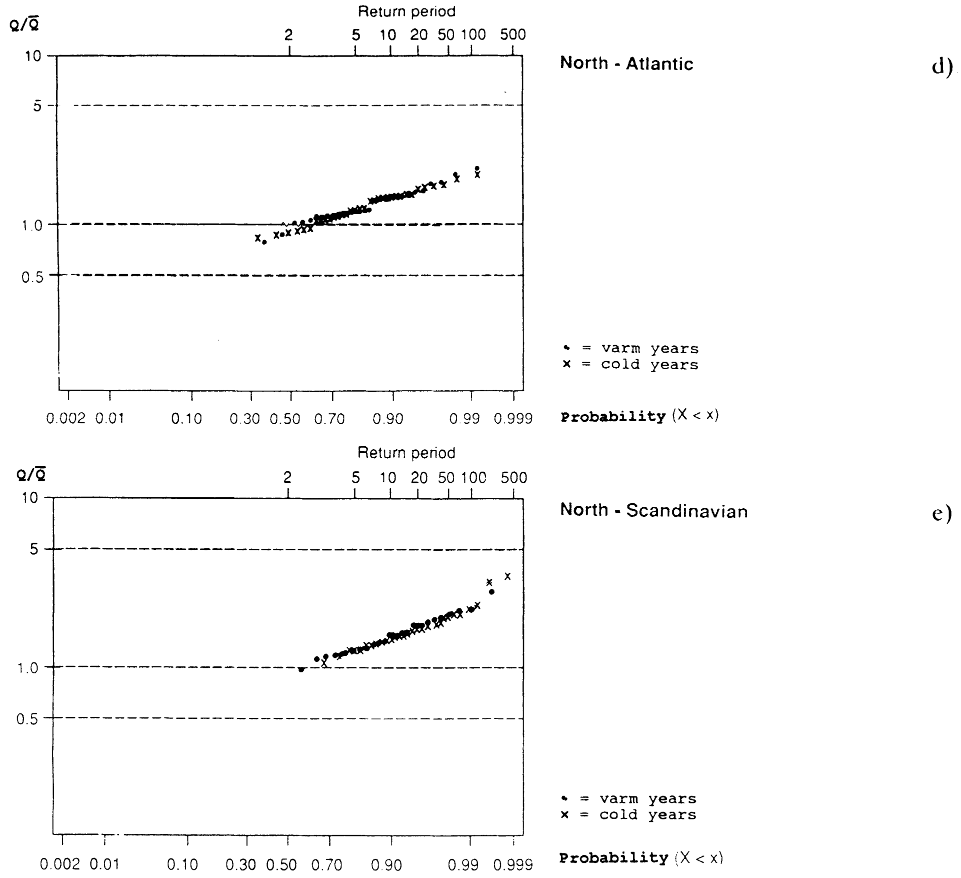

Fig. 2. Cont. Regional exceedance probability curves for different flow regime regions, d), and e).

Conclusion and Discussion

A possible consequence of climate change concerns change in frequency and magnitude of extreme floods. The study has shown that some ideas of the sensitivity of extreme floods to variations in temperature and precipitation can be obtained from observed flood data records by splitting them into sub-series for warm/cold years and wet/dry years, respectively. To allow generalizations the data have further been grouped in accordance with river flow regimes. Two independent approaches were used – partial duration series and regional exceedance probabilities.

The results of the study are most clearly demonstrated by investigating calculated design floods for a certain return period, here the 100-year flood. The analysis shows that this estimated flood is higher when calculated with observations from "warm" years, for which the mean annual temperature was about 0.9 C° higher than for the whole period. The analysis of the extreme flood events based on partial duration series implied that this increase seems to be a result of the increased intensity of the flood events during the warm years (by 10-15% on the average), while the volumes of floods varied only slightly. Due to this increased number of flood events, the probability of observing floods of large magnitudes increases during the "warm" years. During the "cold" years the situation was the opposite, *i.e.* the intensity of the extreme flood events has decreased.

The results of both the analyses of partial duration series and regional exceedance probabilities revealed the same tendency, namely that the changes are the largest for the southern part of the region. This conclusion supports the one made in our previous study of the stability of river flow regimes (Krasovskaia and Gottschalk 1992), which also showed that the greatest changes in the flow regimes during "warm" (or "cold") years occur in the southern parts of the Nordic countries.

For the "wet" years the number of extreme floods increases between 5%-20% compared to the whole period. The decrease during the "dry" years is of the same range. The magnitude of the extreme floods even in this case seems to be only slightly influenced by the variation of precipitation, being around 1-4%. Again it is in the southern part that the changes are the largest.

Studies of the sensitivity of extreme floods to the changes in temperature and precipitation have been undertaken for Norway by Saelthun *et al.* (1990) and for Finland by Vehviläinen and Lohvansuu (1991). It is difficult to directly compare the results of the present study to those presented in these two investigations for several reasons. In both these studies conceptual models have been used to investigate the sensitivity of flow to climate change. Thus, the results rely heavily on the accuracy and relevance of the models used (Vehviläinen and Lohvansuu 1991). Besides, the hydrological model used has not been calibrated with special attention to extremes for optimal fit. In both studies referred to above, the stress has been put on the changes in the magnitude of the extreme flood events and their seasonal distribution, while the possible effects on the intensity of the flood events have not been treated. Studies that are based on some assumed constant changes in temperature and precipitation show very distinct effects of these changes. The results are in many cases obvious without going into model simulations. The impression is that such assumed constant changes highly oversimplify the real situation and the effect of natural variability in time and space. The present study based on observed regional data sets demonstrates much more complicated variation patterns. Possible effects of temperature and precipitation change are in this case not that clearly revealed.

This study is first of all to be considered as a test of applicability of different methods for analyzing changes in extreme floods due to the observed changes in temperature and precipitation. In order to be able to draw any definite conclusions about the behavior of extreme floods in the context of climate change, it is necessary to repeat the analyses for more complete data sets for the Nordic countries as a whole.

References

Gottschalk, L. (1989) Regional exceedance probabilities, *Nordic Hydrology, Vol. 20,* pp. 201-214.

Gottschalk, L., Jensen, J. L., Lundquist, D., Solantie, R., and Tollan, A. (1979) Hydrological Regions in the Nordic Countries, *Nordic Hydrology, Vol. 10,* pp. 273-286.

Krasovskaia, I., and Gottschalk, L. (1992) Stability of river flow regimes, *Nordic Hydrology, Vol. 23(3),* pp. 137-154.

Rasmussen, P. F., and Rosbjerg, D. (1989) Risk estimation in partial duration series, *Water Resources Research, Vol. 25 (11),* pp. 2319-2330.

Rosbjerg, D. (1985) Estimation in partial duration series with independent and dependent peak values, *Journal of Hydrology, Vol. 76(1/2),* pp. 183-195.

Rosbjerg, D., and Madsen, H. (1992) On the choice of threshold level in partial duration series, Nordic Hydrologic Conference, Alta, Proceedings, pp. 604-615.

Saelthun, N. R., Bogen, J., Flood, M. H., Laumann, T., Roald, L. A., Tvede, A. M., and Wold, B. (1990) Climate change impact on Norwegian water resources, NVE, Publ. NoV42, Oslo.

Vehviläinen, B., and Lohvansuu, J. (1991) Effects of climate change on discharges and snow cover in Finland, *Hydrological Sciences Journal, Vol. 36(2),* pp. 109-121.

Received: 14 September, 1992
Revised version received: 3 January, 1993
Accepted: 6 January, 1993

Address:
Irina Krasovskaia,
Hydroconsult AB,
Lergravsvägen 33,
S-263 52 Högnäs,
Sweden.

Lars Gottschalk,
Dept. of Geophysics,
University of Oslo,
P.O. Box 1022 Blindern,
N-0315 Oslo,
Norway.