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Trends and variability in Swedish floods

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Abstract Trend analysis was carried out for time series of annual and seasonal extremes at 65 unregulated discharge stations in Sweden. The stations are clearly not independent, as shown by the occurrence of large floods in many basins at the same time. Neither the results from statistical trend tests nor visual inspection of the data suggest any change in flood frequency. Furthermore, the end period, 1995, was not chosen arbitrarily, since the reason for initiating this study was the many observed floods in recent years.

INTRODUCTION

Floods and droughts cause more damage and kill more people than any other natural disaster (Rodda, 1995). Many floods have occurred during the 1980s and 1990s, both in Sweden and worldwide (see e.g. WMO, 1995). Some possible causes of a change in flood frequency could be changes in climate, land use or water resources management. In Sweden, systematic discharge recording has taken place since 1807 when the first station was established. The objective of this paper is to search for possible flood trends in Sweden, and put floods in recent years into perspective.

METHODS AND SELECTION OF DATA

A national database was compiled for analysis of floods in Sweden. Only unregulated stations of good quality and at least 50 years of recording were selected. The data are generally fairly reliable. There are nevertheless many problems, which could affect the results, such as changes in observation frequency, ice jamming, missing or erroneous observations etc. Extreme floods are particularly uncertain due to extrapolation of the rating curve. Before 1970 almost all readings were made manually, usually once a day, but at some lake outlets readings were made every two or three days, or even once a week. The observation frequency was not always constant between years, not even during a year. The observations have usually been connected by linear interpolation, which underestimates the peak values. Today almost all stations have automatic gauges, giving daily mean flow records. The effect of this inconsistency was studied by resampling the most recent period with complete data for 10 of the lake stations, with a frequency typical for earlier years with sparse observations. The results showed that this is not a major problem, with an average bias in annual maxima of about 2% for the particular basins. However, a few stations were excluded due to this problem.

In addition to visual inspection of the daily discharge data, some simple methods for quality control were tested for selected stations of good quality, using the period

1976–1995. Polynomial interpolation was found to be useful for this purpose. The idea is that a good observation series is smooth in the sense that each value should fit to a curve through its neighbours. For this purpose Neville's algorithm, based on Lagrange's interpolation formula, was used (see Press *et al.*, 1992). For each day a polynomial was fitted through the two observations on each side. The use of four data points corresponds to a cubic polynomial. In general, higher order polynomials should be avoided (Press *et al.*, 1992).

Missing or obviously erroneous observations were estimated or corrected by the same method. The maximum time lengths for this were kept short (Table 1). With these time lengths gaps could be filled in with an efficiency of 99% on average for 10 tested basins with polynomial interpolation and 98% by linear interpolation. The efficiency was measured by R^2 (Nash & Sutcliffe, 1970) only for the independent observations (Fig. 1) which were not used for estimation of the polynomials. More important is that the bias in annual peak values was only −1% by polynomial interpolation but −6% by linear interpolation. Thus, polynomial interpolation was better than simple linear interpolation, at least for sufficiently short observation gaps. It was as good as cubic splines (see Press *et al.*, 1992), which were also tested. It was therefore also used for reinterpolation of old linear interpolations (Fig. 1), further reducing the bias due to the sparse observation frequency, which was used earlier.

Table 1 Maximum length of periods with old linear interpolations, which were re-interpolated by the polynomial interpolation, or missing data which were filled in.

Autocorrelation in Q 1976–1995	Number of days
>0.998	9
0.995–0.998	7
0.990–0.995	5
0.980–0.990	3
0.970–0.980	1
<0.970	0

The final database consisted of 65 stations, covering a total of 4693 station years, with an average of 72 years. The full data set was divided into a northern subset of 41 stations and a southern subset of 24 stations, with the River Dalälven as the dividing line. The data were divided into calendar years, not into hydrological years. Lindström (1993) made a division into hydrological years but found that it had little influence on the results. The series were further divided into spring floods: 1 January–31 July, and autumn floods: 1 August–31 December. The spring floods are primarily snowmelt-induced floods and autumn floods are primarily due to rainfall. Series of annual and seasonal extremes were extracted and normalized to index floods by dividing each value by the average for the whole period.

Trends were searched both by studying time series plots and by statistical tests. The 60 years 1936–1995 were chosen as the reference period. The statistical tests were only carried out for a subset of 26 stations (Fig. 2), which were in operation during the whole period. Trend analysis was performed with a common confidence level of 95%. Two methods were used: a distribution free test, and regression. The distribution free test, here called the *K*-test, is based on ranks and is a modified form of Kendall's tau-

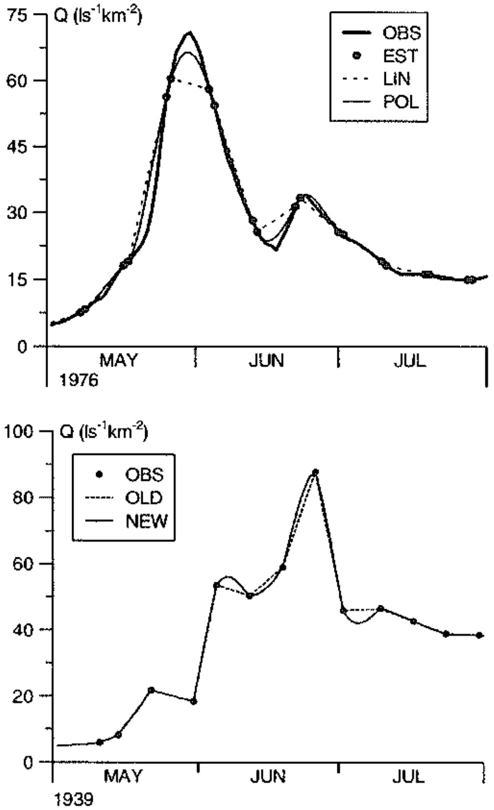

Fig. 1 (a) Examples of linear interpolation (LIN) and polynomial interpolation (POL) *vs* observations (OBS) for hypothetical 5-day gaps. EST = observations used for estimating the polynomials; and (b) examples of reinterpolation (NEW) of old linear interpolations (OLD), together with actual observations (OBS). Reinterpolation was only made when $Q >$ mean discharge (data from Vindeln, River Vindelälven).

test (Hirsch *et al.*, 1982; Hirsch & Slack, 1984). No assumption is required about independent and normally distributed observations. Regression, on the other hand, requires normally distributed data. It is then a more powerful test, and was used by Gustard *et al.* (1989) for flood studies in the FREND project. Logarithmic regression was made to complement the linear one, to study the sensitivity to the assumption of normally distributed data. Logarithmic transformations are common in hydrology (see e.g. Cunnane, 1989). The relative trends by the two methods (linear and logarithmic) are essentially equal, but different results could be expected concerning the significance of the trends. Interstation correlation was estimated (see e.g. Yevjevich, 1972) as a measure of interdependence between the stations.

RESULTS AND DISCUSSION

Some years are characterized by large floods in many basins. Thus, the stations are not independent (Table 2). The spatial interdependence means that particularly spring

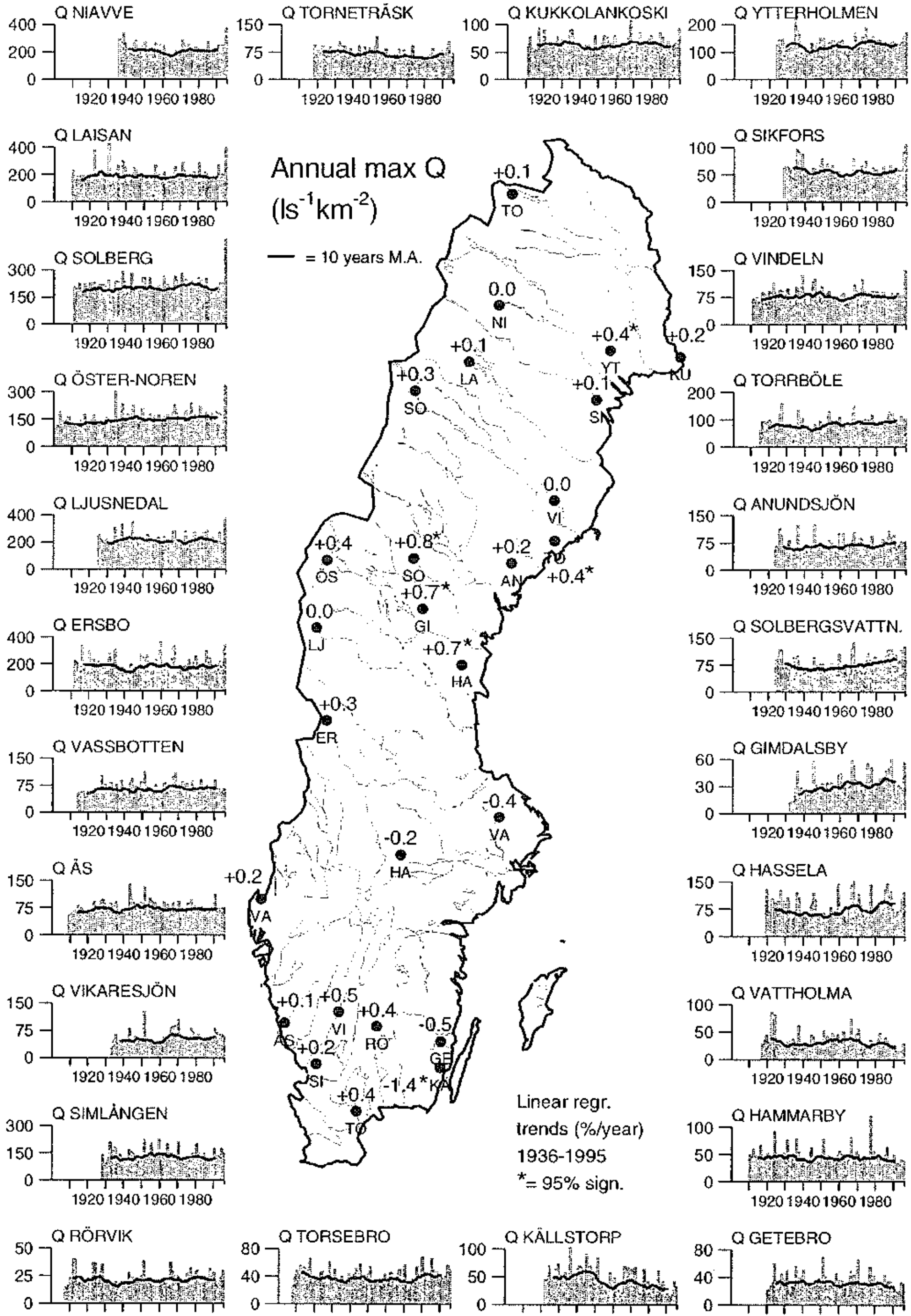

Fig. 2 The highest recorded runoff for each year for 26 selected stations.

Table 2 Estimated average interstation correlation, $\bar{R}$, and the effective number of independent stations, N_E (1936–1995).

	All of Sweden 26 stations		North 16 stations		South 10 stations	
Season:	$\bar{R}$	N_E	$\bar{R}$	N_E	$\bar{R}$	N_E
Annual max.	0.21	4.1	0.32	2.8	0.40	2.2
Spring max.	0.25	3.5	0.33	2.7	0.50	1.8
Autumn max.	0.27	3.3	0.35	2.6	0.43	2.0

floods have a tendency to cover large parts of the country. Examples of years with high floods over large areas are 1924, 1951, 1966, 1967 and 1995. Remarkable years were 1995 with record high values at 14 of the 36 northern stations in operation, and 1951 in the south with records at 5 out of 20 stations.

There were relatively few high autumn floods in the 1970s (Fig. 3). After this followed a period richer than normal in autumn floods. This may have given the impression of a change, particularly in regulated systems where much of the natural spring flood is stored in reservoirs. Seen in a longer perspective, the last 10 years fit in with the natural variability. A high frequency of floods in the 1980s over large parts of

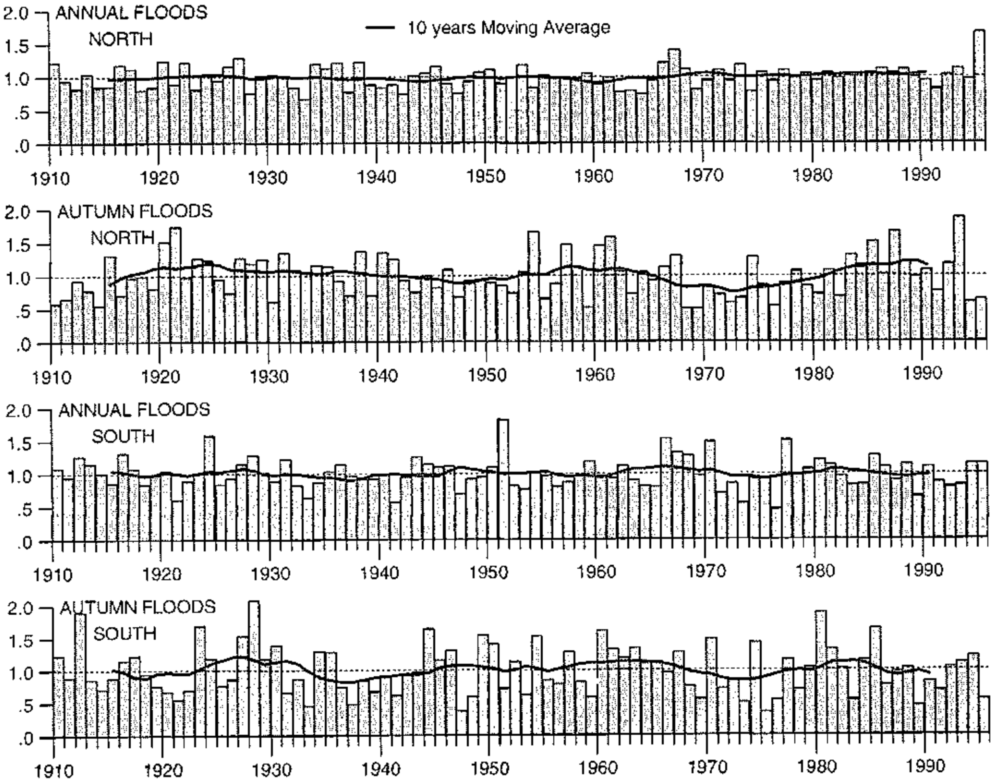

Fig. 3 Average index floods for annual and autumn maximum floods for the northern (41 stations) and southern parts (24 stations) of Sweden.

western Europe was also noted by Gustard *et al.* (1989). On a global scale there have been two major flood periods during the past 200 years: 1861–1888 and 1951–1971 (Yongquan, 1993). These periods can hardly be said to be outstanding in Sweden (Fig. 3).

Neither visual inspection of the data nor trend tests point to any general trend in floods. This agrees with the results by Jutman (1991), who found weak, if any, trends in annual mean runoff in Sweden, and by Hisdal *et al.* (1995) for the Nordic countries, whereas Strupczewski & Mitosek (1998) reported a decreasing tendency for Poland. Similar results, concerning the significance of a trend, were obtained by the distribution free trend test and the two regression methods. Thus, the assumption of normally distributed data, in the linear regression, did not influence the results to any large extent. The statistical tests indicated much fewer significant trends for autumn floods than for annual and spring floods, due to higher variability in autumn floods. The results for spring floods are not presented here since they are essentially the same as for annual floods.

At a 95% level for significance, the tests should indicate trends for some 5% of the 26 samples, if they were completely random. Somewhat higher numbers than this, six for the linear regression test and seven by the two other tests, were found for annual floods during the reference period (Fig. 2). The trends were more often positive than negative. The overall average increase in floods during this period was only about 1% per decade, which is far from being significant. This number can be compared with an average coefficient of variation of 32% for the same period. On average the regression equations explained only 4% of the total variance for 1936–1995. Different subperiods also differed considerably (Table 3). The trend results thus depend on the choice of time period. Furthermore, the series are not independent, since the observations are parallel in time. The sub-period which deviated the most from the expected was 1936–1995. If 1926 was chosen instead as the first year, or if 1985 was chosen as the last year, the number of significant trends decreased. However, the results did not depend too much on the inclusion of 1995. For the period 1936–1994 the number of significant trends (by the K-test) was reduced by one compared to the period 1936–1995. No significant trends were found for regionally combined data consisting of the 41 northern and the 24 southern stations (Figs 3 and 4). Neither did extensions of old data series into modern time show any significant trends (Fig. 5).

Annual averages and annual maxima were significantly correlated (on average 0.5). Variations in annual flow volumes are thus also reflected in the extremes. However, the magnitude and the significance of the trends did not always agree when comparing the results for averages and maxima. Results based on annual averages can thus not be directly transferred to annual maxima.

Table 3 Sensitivity analysis of the trend test of annual maxima (95% level). The number of significant positive, N+, and negative trends, N–, according to the K-test, and the total number of series, Ntot, for different subperiods.

	06–95	16–95	26–95	36–95	46–95	56–95	66–95	76–95	36–55	36–65	36–75	36–85	36–95
N+	1	2	3	6	4	2	0	2	0	0	1	3	6
N–	0	0	1	1	1	1	2	0	0	2	1	1	1
Ntot	1	12	21	26	26	26	26	26	26	26	26	26	26

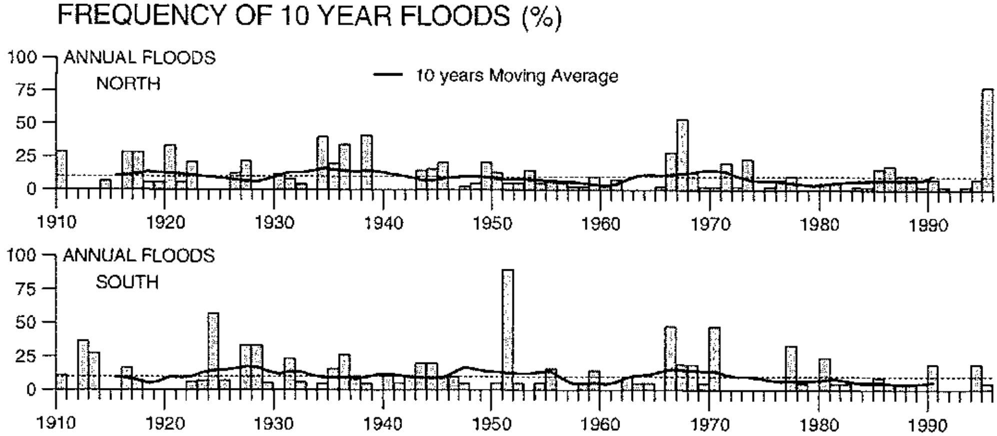

Fig. 4 Frequency of 10 year floods in the northern (41 stations) and southern parts (24 stations) of Sweden. The frequency (%) was computed relative to the number of stations in operation for each year.

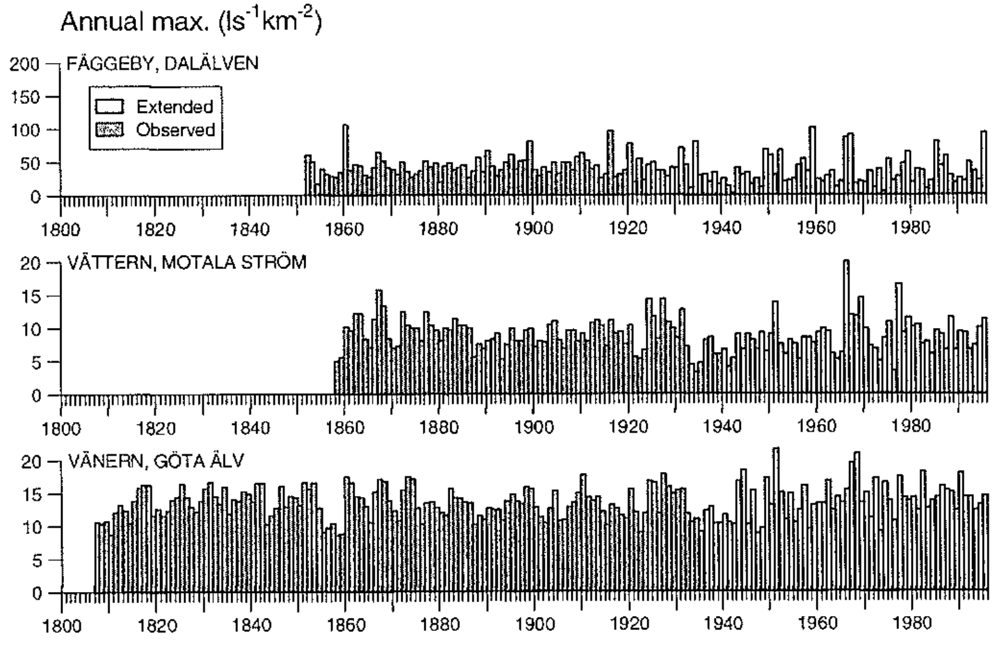

Fig. 5 Observations from the nineteenth century extended by the best correlated series in the database, assuming that they were perfectly correlated in order not to reduce the variance. Fäggeby was extended by the station Ersbo ($r = 0.92$), Vättern by Nömmen ($r = 0.75$), and Vänern was extended by Vättern ($r = 0.75$) and Vassbotten ($r = 0.58$), where r is the estimated correlation coefficient.

CONCLUSIONS

Discharge data from 65 unregulated stations in Sweden were studied, most intensively for the period 1936–1995, although a few stations were also in operation during the nineteenth century. Changes in observation frequency at some lake outlets were found to have little influence on the results. Polynomial interpolation could be used for detection of erroneous data and for filling in short gaps in the observation series. The spatial correlation between observation series was considerable, meaning that floods tend to occur in large parts of the country at the same time. Neither statistical trend tests nor visual inspection of series of annual and seasonal maxima indicate any change in flood frequency. The reason for initiating this study was the many floods in recent years. By choosing 1995 as the period end one could therefore expect slightly more significant trends than in randomly chosen samples.

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REFERENCES

Cunnane, C. (1989) Statistical distributions for flood frequency analysis. *WMO Operational Hydrology Report no. 33, WMO no. 718, World Meteorological Organization, Geneva, Switzerland.*

Gustard, A., Roald, L. A., Demuth, S., Lumadjeng, H. S. & Gross, R. (1989) Flow regimes from experimental and network data (FREND). *Institute of Hydrology, Wallingford, UK.*

Hirsch, R. M., Slack, J. R. & Smith, R. A. (1982) Techniques of trend analysis for monthly water quality data. *Wat. Resour. Res.* **18**(1), 107–121.

Hirsch, R. M. & Slack, J. R. (1984) A nonparametric trend test for seasonal data with serial dependence. *Wat. Resour. Res.* **20**(6), 727–732.

Hisdal, H., Erup, J., Gudmundsson, K., Hiltunen, T., Jutman, T., Bering Ovesen, N. & Roald, L. (1995) Historical runoff variations in the Nordic countries. *NHP Report no. 37, The Nordic Co-ordinating Committee for Hydrology (KOHYNO).*

Jutman, T. (1991) Analys av avrinningens trender i Sverige (Analysis of runoff trends in Sweden, in Swedish). *Hydrology no. 30, Swedish Meteorological and Hydrological Institute, Norrköping, Sweden.*

Lindström, G. (1993) Floods in Sweden—trends and occurrence. *RH no. 6, Swedish Meteorological and Hydrological Institute, Norrköping, Sweden.*

Nash, J. E. & Sutcliffe, J. V. (1970) River flow forecasting through conceptual models. Part I: A discussion of principles. *J. Hydrol.* **10**(3), 282–290.

Press, W. H., Teukolsky, S. A., Vetterling, W. T. & Flannery, B. P. (1992) *Numerical Recipes in FORTRAN. The Art of Scientific Computing*, second edn. Cambridge University Press, Cambridge, UK.

Rodda, J. C. (1995) Whither world water. *Wat. Resour. Bull.* **31**(1), 1–7.

Strupczewski, W. G. & Mitosek, H. T. (1998) Investigation of trend in annual peak flow series. III. Flood analysis of Polish rivers. In: *Proc. Second Int. Conf. On Climate and Water* (ed. by R. Lemmelä & N. Helenius) (Espoo, Finland, August 1998), 264–272. Helsinki University of Technology, Helsinki, Finland.

Yevjevich, V. (1972) *Probability and Statistics in Hydrology*. Water Resources Publications, Fort Collins, Colorado, USA.

Yongquan, W. (1993) Solar activity and maximum floods in the world. In: *Extreme Hydrological Events: Precipitation, Floods and Droughts* (ed. by Z. W. Kundzewicz, D. Rosbjerg., S. P. Simonovic & K. Takeuchi) (Proc. Yokohama Symp., July 1993), 121–127. IAHS Publ. no. 213.

WMO (1995) Climate system monitoring—the global climate system review (June 1991–November 1993). *WMO no. 819, World Meteorological Organization, Geneva, Switzerland.*