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Long-term changes of the river runoff in Latvia

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The study of changes in river discharge is important for the development of efficient water resource management systems, as well as for the development and validation of climate change impact models. The discharge regime of rivers and their long-term changes in Latvia were investigated. Four major types of river discharge regimes, which depend on climatic and physico-geographic factors, were characterized. These factors are linked to the changes observed in river discharge. Periodic oscillations of discharge intensity, and low- and high-water flow years are common for the major rivers in Latvia. A main frequency of about 20 and 13 years was estimated for the studied rivers.

Introduction

Considering the increasing human impact on the environment, studies of environmental changes are of outmost importance. Long-term observations of hydrologic systems provide time series of evapotranspiration, precipitation and river discharge. These data series can be analysed from different points of view. For example, the study of the hydrological cycle is important in the investigation of climatic variation and in hydrological applications (Arnell 1992). Considerable attention has been paid to the study of global climate change, to relations between global processes of atmospheric circulation (NAO, ENSO) and to the hydrological cycle (Perry *et al*. 1996, Amarasekera *et al*. 1997, Simpson and Colodner 1999), as well as the regional impacts of global climatic changes (Gleick 1986). Future climatic changes may have a substantial impact on river discharge patterns, as well as on extreme events, their magnitude and probability of occurrence (Krasovskaia and Gottschalk 1993). River discharge data can also be used to validate hydrological cycle calculations in climate models (Zeng 1999).

River discharge time series have been extensively studied worldwide (Molenat *et al*. 1999,

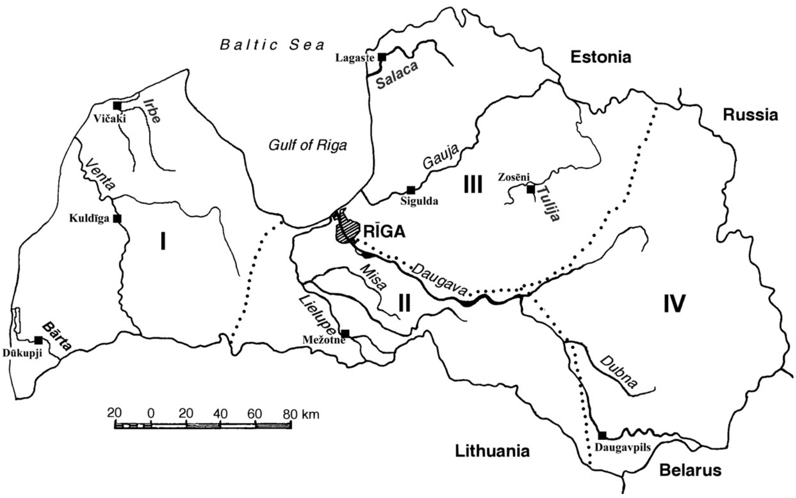

Fig. 1. Hydrologic regions of Latvia (I–IV) and discharge (■) study sites.

Costa and Foley 1999, Lins and Slack 1999). The relevant trends regarding global climate changes have been identified in Nordic countries (Kite 1993, Vehviläinen and Huttunen, 1997 Rosenberg *et al*. 1999). In Finland, climate change may result in an increase of mean discharge by 20%–50% (Vehviläinen and Lohvansuu 1991). Extensive study of river discharge trends in the USA identified that the USA is becoming wetter with less extreme events (Lins and Slack 1999).

Commonly, river discharge patterns have been studied in terms of linear trend analysis, even though they can be much more complex. Analysis of river discharge patterns is important for the Baltic countries, which are located in a climatic region directly influenced both by atmospheric processes in the northern Atlantic and by continental impacts from Eurasia.

The earliest observations of river discharge in Latvia can be dated back to the 19th century for the Daugava river, and long series of data have been accumulated. Studies conducted on river discharge trends in Estonia confirm the importance of such analysis (Jaagus *et al*. 1998). Long-term stream flow analysis is essential for effective water resource management and therefore has immense socio-economic significance. Discharge analysis in respect to global climatic changes is also presently important considering the predicted changes in this region.

The aim of the present study is to analyse the long-term changes of river runoff in Latvia.

Materials and methods

The study area covered the entire territory of Latvia (Fig. 1), but reference sites of rivers in neighbouring areas were also used.

In Latvia, there is a dense network of rivers flowing through Quaternary sediments. The total number of rivers is 12 500, of which only 17 are longer than 100 km. The total length of rivers is ~37 950 km and the mean density of the river network is 588 m per 1 km^2. The average annual runoff of rivers is about 35 km^3, of which more than 50% forms in neighbouring countries. The hydrological regime in rivers is influenced not only by the climate (precipitation and air temperature), but also by factors such as geomorphology, geological structure, soil composition, and land-use patterns (Table 1). The coverage of lakes and wetlands in river basins also affects the river stream flow. More than 90% of the total runoff in Latvia is through the five largest rivers. In general, the dominance of natural habitats indicates a rather low level of anthropogenic impact.

The climatic conditions of Latvia are dominated by transport of cyclonic air masses from the Atlantic Ocean, leading to comparatively high humidity, uneven distribution of atmospheric precipitation through the year, mild winters and moist summers. In general, the spatial heterogeneity of the climate of Latvia is determined by physio-geographical features, such as upland relief, distance to the Baltic Sea, and cov-

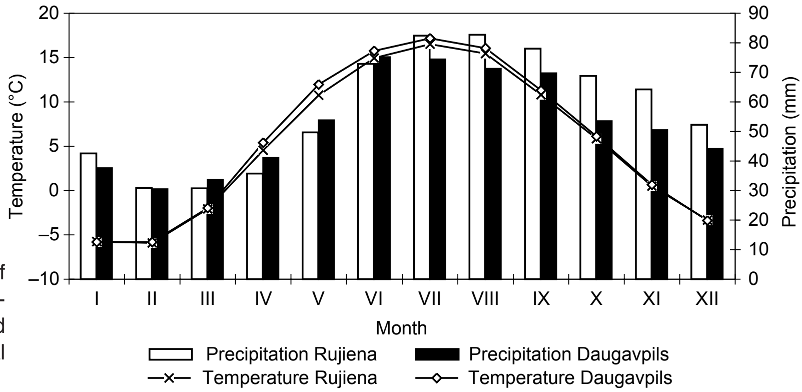

Fig. 2. Monthly variability of temperature and precipitation for Daugavpils (SE) and Rujiena (NNE) meteorological stations.

erage of forests and mires. More precipitation is common for uplands (> 200 m from sea level), and differences between regions can reach up to 250 mm annually. For climate characterization monthly temperature and precipitation of Daugavpils (in SSE of Latvia) and Rujiena (in NE of Latvia) meteorological stations have been represented (Fig. 2). For centenary trend estimation of the air temperature and precipitation, data from the Meteorological Station Riga University were used. Data used in this study were obtained from the Latvian Hydrometeorological Agency.

Discharge measurements covered the last 60 years for the Gauja river and 118 years for the Daugava river. For trend analysis, mean annual discharge values calculated as arithmetic means from monthly records were used.

The stream flow data before analyses of variability have been tested by the Fisher test for data homogeneity (Table 2). The length of

Table 1. Characteristics of the studied rivers.

River	Basin size (km^2)	Length (km)	Water runoff (km^3/year)	Forest area (%)	Bog area (%)	Agricultural area (%)
Daugava	87900	1005	20.4	43	5	50
Lielupe	17600	119	3.6	22	3	71
Venta	11800	346	2.9	32	5	62
Gauja	8900	452	2.2	47	5	48
Salaca	3420	95	0.95	34	15	45
Barta	2020	98	0.63	–	–	–
Irbe	2000	32	0.44	–	–	–
Tulija	57	15	0.018	–	–	–

Table 2. Results of Fisher test statistics.

River	N	SD	$F_{empirical}$	$F_{theoretical}$	p
Salaca, 1927–1959	33	10.51	1.10	1.76	0.05
Salaca, 1960–1999	40	10.00			
Gauja, 1940–1959	20	14.55	1.87	1.99	0.05
Gauja, 1960–1999	40	19.91			
Daugava, 1920–1959	40	115.35	1.02	1.69	0.05
Daugava, 1960–2000	41	116.50			
Lielupe, 1921–1959	39	20.95	1.60	1.71	0.05
Lielupe, 1960–1998	39	16.58			
Venta, 1920–1959	40	17.33	1.45	1.70	0.05
Venta, 1960–1999	38	20.85			
Nemunas, 1920–1959	40	94.91	1.23	1.85	0.05
Nemunas, 1960–1986	27	85.59			

observation has been divided into two periods that differ by intensity of agricultural activities. Obtained results indicated that time series of the river flow are homogenous ($F_{empirical} < F_{theoretical}$, $p = 0.05$) for all selected rivers.

For the calculation of the periodic changes (oscillation) of discharge, moving average (step 5 and 10 years) values of discharge data as well as integral curves were utilized. The use of integral curves, which depict differences in discharge for each study year in comparison with mean values for all observation periods, allows identification of the pattern of discharge changes. In the calculation, ratio K was used:

$$K = Q_i/Q_0$$

where Q_i is a discharge in year i and Q_0 is a mean discharge for the entire period of observation.

Using this approach, we produced the integral curve by summing these deviations $\sum(K - 1)$. By integration of the deviations, the amplitude of the oscillations increases proportionally to the length of the period, with one-sign deviations in the row. The analyses of integral curves allow precise identification of significant change points of low-water and high-water discharge periods. High-water discharge periods are considered to be years for which $K > 1$, and low-water flow periods are indicated by a $K < 1$. For the data treatment, the Excel, SPSS, and Multimk software packages were used.

The multivariate Mann-Kendall test (as described by Hirsch *et al.* 1982, Hirsch and Slack 1984) for monotone trends in time series of data grouped by sites was chosen for the determination of trends, as it is a relatively robust method concerning missing data, and it lacks strict requirements regarding data heteroscedasticity. The Mann-Kendall test was applied separately to each variable at each site, at a significance level of $p < 0.5$. The trend was considered as statistically significant at the 5% level if the test statistic was greater than 2 or smaller than –2 (Hirsch and Slack 1984).

Spectral analysis has been applied for the normalized river stream flow data. The spectrum of the stream-flow time series was calculated using the autocorrelation function and evaluated with theoretical spectra afterwards.

Results and discussion

Depending on the discharge regime, the river basins in Latvia can be grouped into 4 hydrological regions (Fig. 1). The hydrological regions differ in the seasonal river discharge variability in spring and autumn, by the relative proportion between spring and autumn floods (Fig. 3), and also in other factors (precipitation, evapotranspiration, run-off, temperature):

Type I. The Venta river and small rivers along the coast of the Baltic Sea. The rivers in this region have two main discharge peaks, the first during the spring snow melt and the second in the late autumn during intensive rainfall;

Type II. The Lielupe river and small rivers in the central part of Latvia. This group of rivers receives the major part of their discharge from direct surface run-off, spring floods dominate, and the role of permanent water discharge during the year is comparatively low (~ 40%);

Type III. Basins of the Salaca river, Gauja river and small rivers along the Gulf of Riga coast. This group of rivers is characterised by substantial snowmelt floods and comparatively smaller (than type I) rain floods in autumn. 50%–60% of the total run-off takes place in spring;

Type IV. The Daugava river and its largest tributaries (the Aiviekste and Dubna) in Latvia. More than half of the river discharge takes place during spring floods, and the water discharge pattern is characterised by steep fluctuations of water discharge intensity.

Differences in annual precipitation in Latvia range from 63% to 150% in comparison with the mean values. More precipitation occurs in the warm period of the year (April–October), reaching 63%–70% of the annual total. Mean air temperature decreases in the direction from west to east. Inter-annual temperature variability (mean value 22.5°, maximum 34°), as well as intra-annual variability has comparatively small significance (Lizuma and Briede 2001).

Changes in river discharge were determined

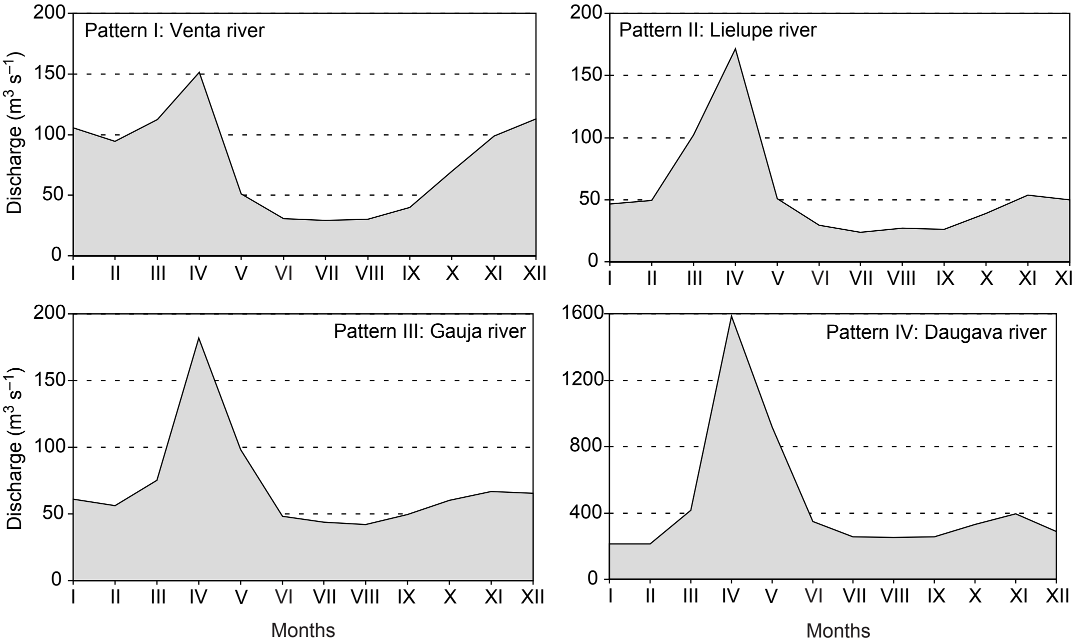

Fig. 3. Patterns of seasonal changes of river discharge in major rivers in Latvia.

using linear trend analysis with commonly used approaches in the study of river discharge. Figure 4 and Table 3 show that the discharge trends in rivers of Latvia and the north-eastern part of the Baltic Sea are minimal: the discharge has significantly increased for the Venta, Gauja, Barta, Irbe and Tulija rivers, but the changes are insignificant and decreasing for all of the other studied rivers (the Daugava, Lielupe and Salaca in Latvia, and for comparison, also the Neman, Narva and Neva). It is also reviewed that river discharge is characterized by stronger increase if the period of trend analyses is made for the last 50 years. It should be mentioned that discharge trends and trends for precipitation and temperature are similar for the II, III, IV hydrological regions. Regarding the Venta river, located in the type I hydrological region, a positive trend of discharge is more expressed.

The observation period for the Meteorological Station Riga University is more than 150 years (Fig. 5). At the same time there is no information about technical aspects of precipitation measurements, which have been done before 1892. It is stated that a Nipher shielded gauge was installed for the meteorological station of

Table 3. Significance test for temporal changes of water discharge for rivers in Latvia. The trend can be considered as statistically significant at the 5% level if the test statistics are greater than 2 or smaller than –2.

River/station	Years	Mann-Kendall test statistic	*p*-value of one-sided test
Daugava/Daugavpils	1922–1998	–1.087	0.139
Venta/Kuldiga	1920–1999	2.127	0.017
Lielupe/Mezotne	1921–1998	–1.765	0.039
Gauja/Sigulda	1940–1999	2.2579	0.012
Salaca/Lagaste	1927–1999	0.7620	0.223
Barta/Dukupji	1950–1999	2.3505	0.009
Irbe/Vicaki	1955–1999	2.1912	0.014
Tulija/Zoseni	1961–1998	2.8538	0.002

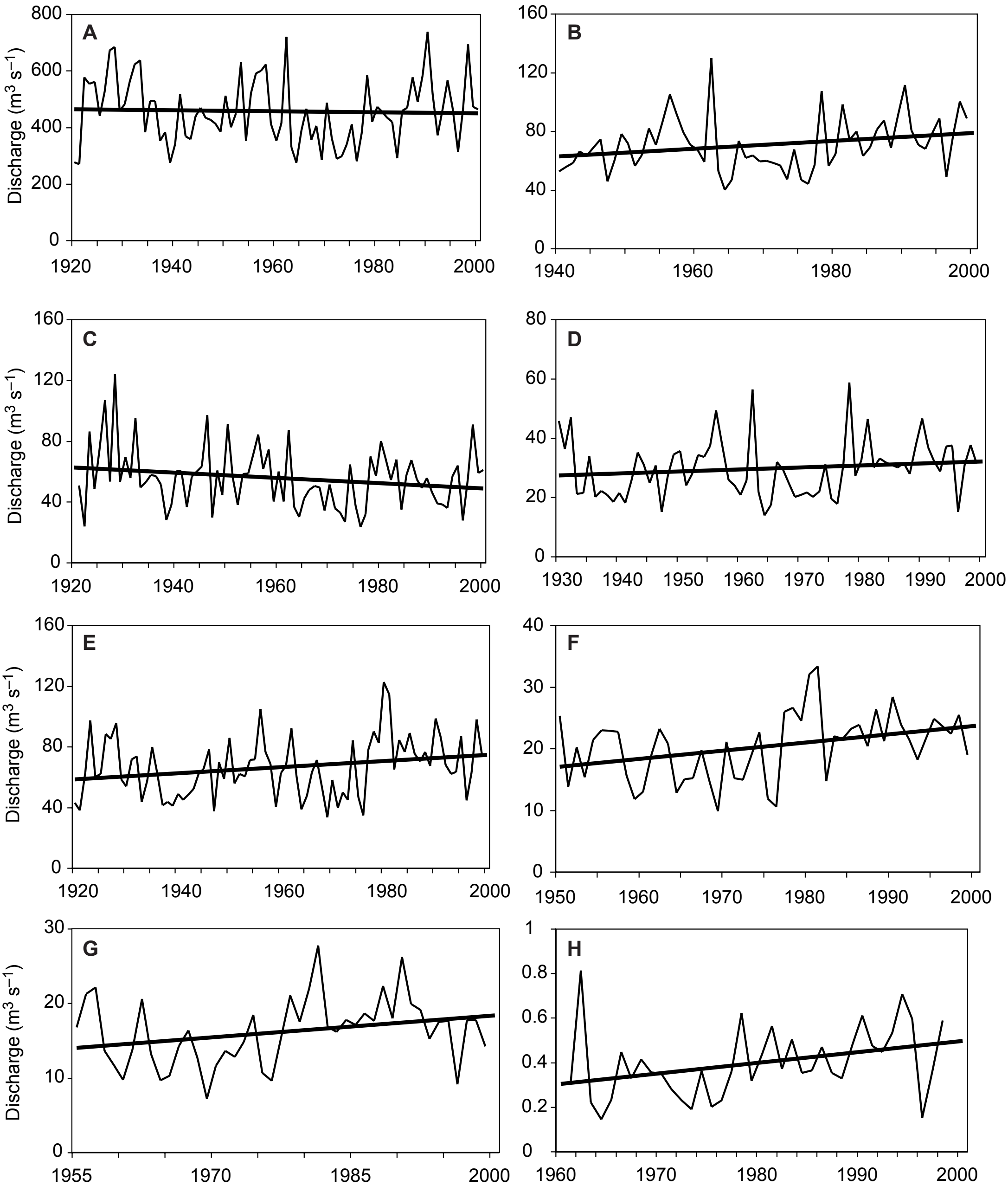

Fig. 4. Long-term changes of river discharge in Latvia. — **A**: Daugava river, Daugavpils; — **B**: Gauja river, Sigulda; — **C**: Lielupe river, Mezotne; — **D**: Salaca river, Lagaste; — **E**: Venta river, Kuldiga; — **F**: Barta river, Dukupji; — **G**: Irbe river, Vicaki; — **H**: Tulija river, Zoseni.

the University of Latvia in 1893. Due to a lack of information, the earlier period is not included for the trend analyses. During the last century, the mean annual temperature has increased by about 0.8–1.4 °C, and the total annual precipitation by about 7.5 mm every year (Lizuma 2000).

Using moving average values (in this case with step 10 years), good coherence is seen between changes in annual precipitation at the Meteorological Station Riga University and discharges of the largest rivers (Daugava and Nemunas) flowing into the eastern coast of the

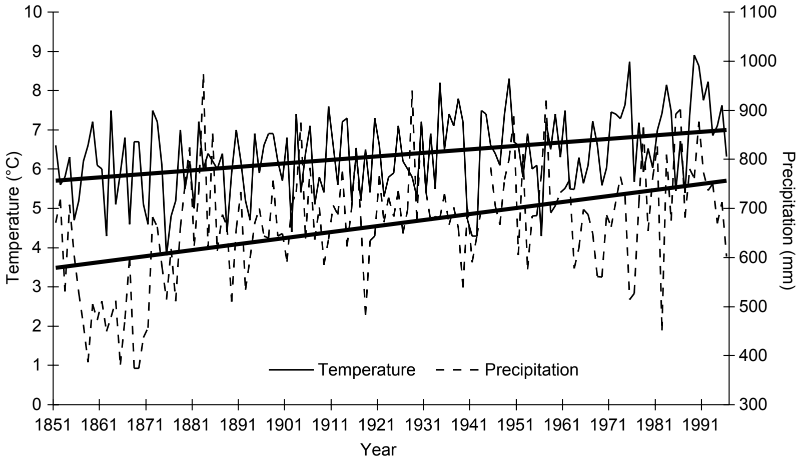

Fig. 5. Long-term changes of temperature and precipitation for the Meteorological Station Riga University.

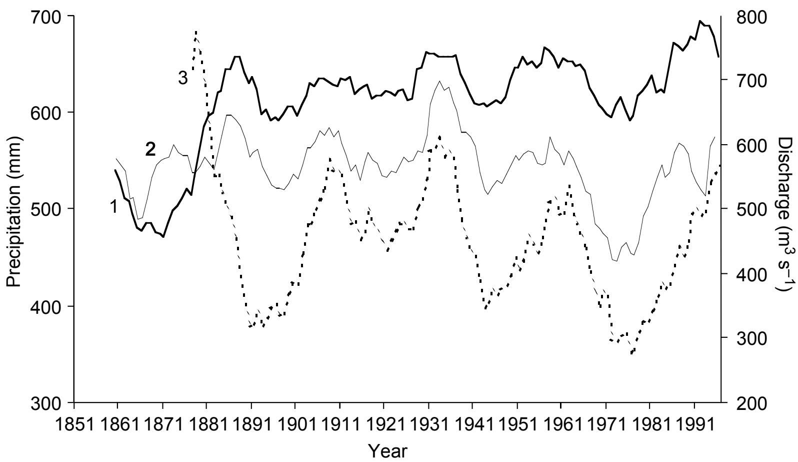

Fig. 6. Changes (10-year step moving mean) of annual discharge and precipitation (1851–1996): — 1: precipitation (Station Riga University); — 2: Nemunas river; — 3: Daugava river.

Baltic Sea for the last hundred years (Fig. 6). Figure 6 also indicates periods with low- and high-water levels, and the presence of regular cyclic processes. Close relationships between meteorological data and discharge can be found when studied for periods longer than 60 years.

The use of integral curves allows better identification of oscillation patterns. Figure 7 shows integral curves for water discharge in the five largest rivers in Latvia. Differences are seen between the Lielupe and the other four rivers in Latvia, and in all rivers there is an apparent difference between observations before and after 1920. For example, in the Lielupe river, water discharge decreased from 1986 to 2000, in contrast to the other rivers that showed a stable increasing tendency. In 1996 the water discharge reached the lowest value during the last ten years in rivers in Latvia (Fig. 7). The difference in flow patterns between the Lielupe river and other rivers in Latvia can also be explained by the fact that the sampling station in the Lielupe, which is situated quite upstream (110 km) and thus reflects slightly more than 50% of the total river discharges. The Lielupe river basin has been moderately affected by melioration and by construction of various hydro-technical obstructions (dams, ponds, etc.) (Kraukle 1987). Also, agricultural activities influence the water flow regime in this river.

General patterns of the periodicity of water flow regime in several major rivers in Latvia and in neighbouring countries are summarised in Table 4. The duration of high water flow periods for the last half century was 27 years in the case of the Daugava river and up to 33 years for the Salaca, Venta and Gauja rivers. The number of low water-flow periods was 23 and 17 years for the Daugava and the other rivers, correspond-

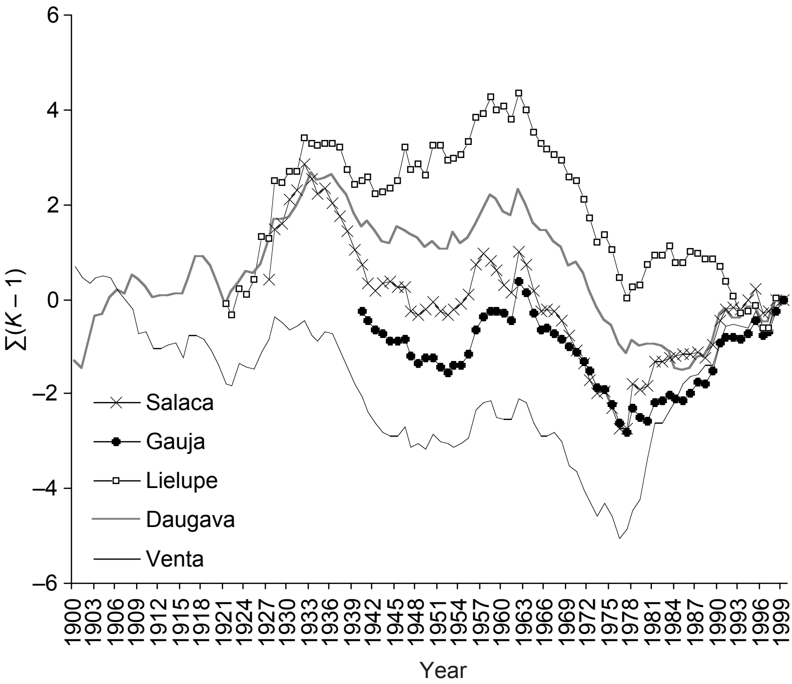

Fig. 7. Normalized integral curves for coefficients of the annual run-off of the rivers in Latvia (integral curve is produced by summing these deviations $\Sigma(K-1)$).

ingly. During the same time period in the Lielupe river, duration of the high water flow period was 21 years and the low water flow periodicity was 29 years.

Figure 8 shows the spectrum of the normalised time series (Tukey window 20) for the largest rivers in Latvia. A low low-order harmonics at frequencies of 0.05 and 0.07 cycles/year, corresponding to periods of about 20 and 13 years, supports the suggestion about periodic oscillations of river discharge regime.

Goudie (1992) described sinusoidal changes of river discharge in Eastern Europe. Short-term fluctuations with a mean duration 4–6 years have been previously found in Estonia and Finland (Hiltunen 1994, Jaagus 1995). Approximately a 20-year periodicity has been suggested in earlier studies for rivers in the Baltic region and Eastern Europe (Glazacheva 1988), along with a period of about 20 to 50 years for monthly mean precipitation and water levels, which may be the result of interference of the precipitation and temperature regimes. In the previous studies, a 26-year periodicity of the flow of the Daugava river was considered as the main period, which includes smaller cycles of 2, 6 and 13 years (Glazacheva 1988). One possible explanation of such long-term oscillations can be linked to changes in solar activity, to circulation patterns of air masses in the northern hemisphere and also to variability in cosmic ray fluxes as found in the studies of Svensmark and Friis-Christensen (1997).

Table 4. Changes of low and high discharge periods for the largest rivers in Latvia.

River	High discharge periods	Q_{mean} ($m^3 s^{-1}$)	$K = Q_i/Q_{mean}$	Low discharge periods	Q_{mean} ($m^3 s^{-1}$)	$K = Q_i/Q_{mean}$	Observation period (years)
Daugava	49	544.6	1.18	69	411.0	0.89	118
Venta	39	74.0	1.13	61	58.1	0.89	100
Lielupe	38	66.7	1.20	39	46.0	0.83	77
Salaca	39	37.9	1.25	34	24.0	0.79	73
Gauja	32	82.2	1.17	28	59.2	0.84	60

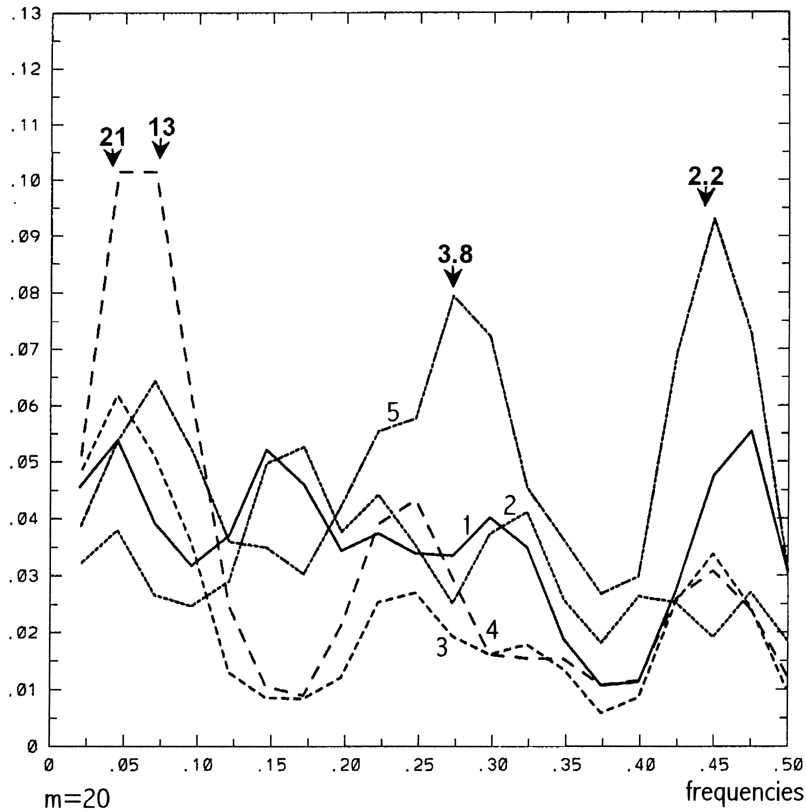

Fig. 8. Streamflow spectra for the largest rivers in Latvia (Tukey window 20).

The study showed that, due to the oscillation of water discharge, cyclic processes should be considered rather analysis in terms of linear trends.

Conclusions

The river discharge in Latvia much depends on climatic and physico-geographic factors and four major types of river discharge regimes can be identified. Changes of discharge are minimal: the discharge has significantly increased only for rivers Venta, Gauja, Barta, Irbe and Tulija, but the changes are insignificant and decreasing for all of the other studied rivers. River discharge can be characterized by stronger increase if period of trend analyses is taken for the last 50 years. At the same time, periodic changes from low-water periods to high-water periods, lasting longer than decades, are significant. Oscillations of the discharge intensity, and low- and high-water flow years are common for the major rivers in Latvia. A main frequency of about 20 and 13 years was estimated for the studied rivers.

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