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Patterns of river discharge: long-term changes in Latvia and the Baltic region

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Abstract Studying changes in river discharge and flood regimes is important in order to learn effects of the climate change. Periodic oscillations of discharge intensity and low- and high-water flow years are common for major rivers in Latvia as well as for those in the Baltic region. This investigation of changes in river discharge and flooding events in Latvia was undertaken in order to compare them with those occurring in the neighbouring countries. Changes in maximal and minimal discharges for major rivers in Latvia have been studied and changes of extreme discharge regimes have been calculated.

Keywords *Discharge, long term variability, trends, Latvia.*

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INTRODUCTION

Performing periodic analysis of changes in the river discharge regimes is of vital importance in order to develop a well-balanced water resource management system, but in the light of climate changes, process analysis of long-term observations can support development of new prognostic models. Long term changes in the river discharges are analysed in order to study climate variability and climate change impacts (Amarasekera *et al.* 1997); also to study the character, the return periods and impacts of extreme hydrological processes (floods, droughts) and to validate the climate change modelling results. As far as the hydrological regimes of rivers being affected by a multitude of factors, such as, climate change (increase of temperature, changes of precipitation regime etc), changes in large scale atmospheric circulation, as well as human activities (development of hydro technical constructions), to identify the driving processes which cause changes and estimate their possible impacts, it is important to study long term changes from regional perspective. Climate change may have substantial impact on river discharge patterns, as well as on extreme events, their magnitude, probability and frequency of their occurrence (Krasovskaia & Gottschalk 1993; Northrop 2004).

River discharge time series and flood return periods as well as flooding risks have been extensively studied worldwide (Molenat *et al.* 1999; Costa & Foley 1999; Lins & Slack 1999; Benito *et al.* 2003). The relevant trends regarding global climate changes have been identified in Nordic countries (Rosenberg et al. 1999; Vehviläinen & Huttunen 1997; Lindstrom & Bergstrom 2004). Analysis of river discharge patterns and flood risk is especially 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 climatic impacts from Eurasia.

The earliest observations of river discharges in Latvia can be traced back to the 19th century for the River Daugava when already extensive series of data were gathered and compiled. Studies conducted on river discharge trends in Poland, Estonia and Lithuania confirmed the value of such analysis (Jaagus *et al.* 1998; Strupczewski *et al.* 2001; Reihan *et al.* 2007). It was recognized that the long-term stream flow and flooding event analysis is essential for effective water resource management and, for that reason could be of enormous socio-economic significance. Performing discharge and flood return period analysis in respect to global climatic changes has also been deemed of a major value especially considering the predicted changes in this region. The aim of the present study is to analyse the long-term changes of river discharge and flood periods in the Baltic region, but especially in Latvia.

METHODS

The area of study comprised of the entire territory of Latvia (Fig. 1), however references to river sites in neighbouring countries were also used (Neva and Narva – Russia; Nemunas – Lithuania, Pärnu – Estonia). The hydrological regimes of rivers in Latvia have been 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.

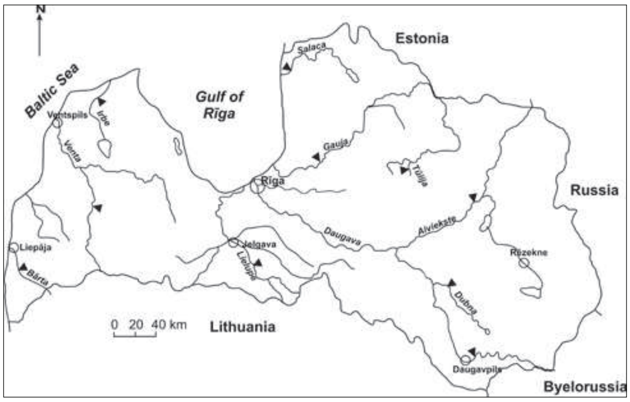

Fig. 1. The location of river gauging stations in Latvia in this study (▲ – river discharge study sites).

Data used in this study were obtained from the Latvian Environmental, Geological and Hydrometeorological Agency and they covered data not only on rivers in Latvia, but also in other countries in the Baltic region. For trend analysis, mean annual discharge values calculated as arithmetic means from monthly records were used. For the calculation of the periodic changes (oscillations) of discharge, moving average (step 6 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 period, allowed identify the patterns of discharge changes. In the calculation, ratio K was used:

$K = \frac{Q_i}{Q_0}$ where: Q_i - discharge in year i; Q_0 – mean discharge for the entire period of observation.

Using this approach, the integral curve was produced by summing these deviations $\sum(K-1)$. By integration of the deviations, the amplitude of the oscillations increased proportionally to the length of the period, with one-sign deviations in the row. The analyses of integral curves allowed identify precisely the significant change points of low water and high-water discharge periods. High-water discharge periods were considered to be years for which K > 1, and low-water flow periods were indicated by a K < 1.

Spectral analysis of the river discharge changes has been done using spectral analysis and constructing periodograms (Pekarova *et al.* 2003). A periodogram is a plot of frequency and ordinate pairs for the studied time period. The graph converts a time series of discharge into a set of sine waves of various frequencies and shows the frequency spectrum. The periodogram (Pekarova *et al.* 2003) is calculated according to:

$$I(\lambda_i) = \frac{1}{2\pi n}\left[\sum_{n-1}^{n} x_t e^{-it\lambda}\right]^2 =$$

$$\frac{1}{2\pi n}\left\{\left(\sum_{n-1}^{n} x_t \sin t\lambda_j\right)^2 + \left(\sum_{n-1}^{n} x_t \cos t\lambda_j\right)^2\right\}$$

For data treatment, the Excel, SPSS, and MultiMK software packages were used. For calculation of the distribution, EasyFit 4.0 has been used.

The multivariate Mann-Kendall test (as described by Hirsch *et al.* 1982; Hirsch & 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 $p<0.05$. The trend was considered as statistically significant at the 5 % level if the test statistic was greater than 1.65 or less than -1.65 (Hirsch & Slack 1984).

RESULTS AND DISCUSSION

The character of changes of the river discharge in Latvia as well as in the Baltic region (including rivers in Estonia, Lithuania and western part of Russia) reflect a profile of processes affecting discharge formulation in corresponding hydrological regions, but also, to a significant degree, the ongoing processes of the climate change.

Within this study the changes of river discharge regime in the Baltic region has been studied using Latvia as an example, and comparing the main findings with the discharge patterns in other countries. The hydrological regime of rivers in this study area differed in the seasonal river discharge variability in spring and autumn, in terms of the relative proportion between spring and autumn floods, but also has been influenced by other factors such as precipitation, evapotranspiration, runoff, and temperature.

Changes in river discharge were determined using linear trend analysis with commonly used approach in the study of river discharge (Rosenberg *et al.* 1999; Vehviläinen & Huttunen 1997; Lindstrom & Bergstrom 2004; Klavins & Rodinov 2008). Table 1 shows the discharge trends in rivers of Latvia and the north-eastern part of the Baltic Sea: the discharge has significantly increased for rivers Daugava, Gauja, Narva, Pärnu, Salaca, Dubna, Irbe and Abava for period 1961–2000, but the changes are increasing for all of the other studied rivers for the same observation period. For all observation periods, the linear trend analysis showed that for River Nemunas statistically significant decrease of discharge can be observed, but for all other rivers the trends of changes statistically were not significant.

Changes of river discharges can be assessed analysing not only long term changes, but also changes of seasonal river discharges (Fig. 2). As it can be seen most of the changes of river discharge take place in the late winter/autumn/summer seasons. The same pattern is common also for other rivers of the Baltic region.

It was also evident that river discharges were characterized by stronger increase, if the period of trend

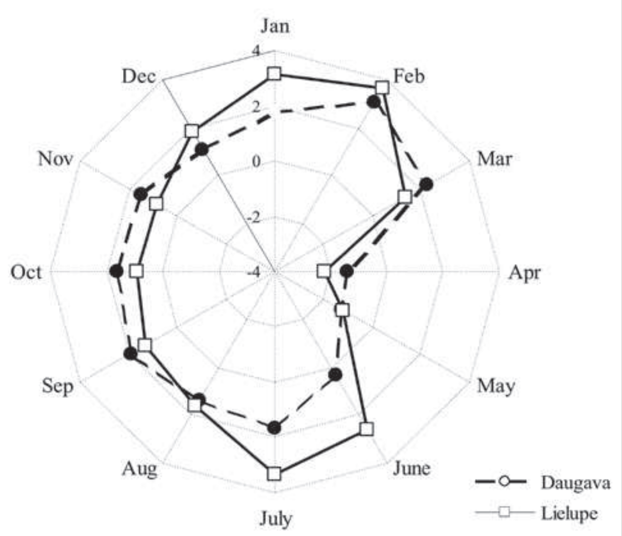

Fig. 2. Long-term trend (1961–2006) of seasonal discharge changes for rivers of Latvia after Mann–Kendall test criteria (the trend can be considered as statistically significant at the 5 % level if the test statistics are greater than 1.65 or less than –1.65).

Table 1. Significance test for temporal changes of water discharge for rivers in the Baltic region.

River	Period of observation	Normalised test statistic	p-value (one-sided test)	Period of observation	Normalised test statistic	p-value (one-sided test)
Neva	1881-2000	-0.68	0.247	1961-2000	1.08	0.139
Nemunas	1896-2006	**-2.90**	0.002	1961-2006	0.03	0.489
Daugava	1881-2006	0.57	0.286	1961-2006	**2.53**	0.006
Venta	1898-2006	1.29	0.098	1961-2006	0.41	0.342
Narva	1902-2002	-0.87	0.191	1961-2002	**2.14**	0.016
Pärnu	1922-2002	0.27	0.394	1961-2002	**2.27**	0.012
Lielupe	1921-2006	-1.08	0.141	1961-2006	1.64	0.051
Salaca	1927-2006	1.06	0.146	1961-2006	**2.66**	0.004
Gauja	1940-2006	1.51	0.066	1961-2006	**2.06**	0.020
Dubna	1948-2006	1.38	0.084	1961-2006	**2.41**	0.008
Barta	1950-2006	0.98	0.164	1961-2006	0.84	0.200
Irbe	1955-2006	1.40	0.080	1961-2006	**1.68**	0.047
Tulija	1961-2006	0.82	0.205	1961-2006	0.82	0.205
Abava	1965-2006	**1.70**	0.044	1961-2006	**1.70**	0.044

* The trend can be considered as statistically significant at the 5 % level if the test statistics are greater than 1.65 or less than –1.65.

analyses is reduced to the last 50 years. It should be mentioned that discharge trends and trends for precipitation and temperature were more pronounced for rivers more distant from seacoast. Regarding the River Venta, located more closely to the Baltic Sea, a positive trend of discharge was more pronounced. The long-term trend of seasonal river discharge indicated that most of the increases happened during the winter season (Fig. 2). The river discharges (for example, Daugava, Venta, and Lielupe rivers) in the winter (December–February) showed a significantly increasing trend, while no trend was detectable in other seasons. A particularly significant increase in winter discharge could be observed during the recent two decades. The same pattern was common also for other rivers of the Baltic region.

As a driving factor affecting river discharge processes, can be considered changes of precipitation and, for rivers in the Baltic region, a good coherence (using moving average values with step 6 years), could be seen between changes in annual precipitation at the Meteorological Station Riga-University and discharges of the largest rivers in Latvia (Fig. 3) and in the Baltic region.

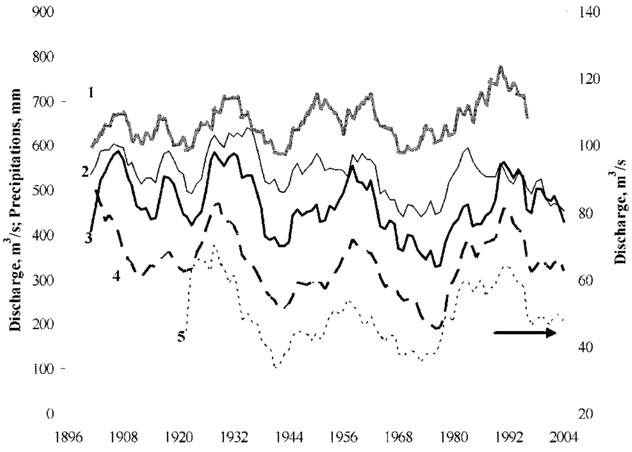

Fig. 3. Long term changes of precipitations and mean annual discharge of the rivers in Baltic region: 1 – precipitations (Station Rīga-University); 2 – Nemunas; 3 – Daugava; 4 – Narva; 5 – Pärnu. Data were smoothed with a six–year moving average.

The Fig. 3 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 observations are carried out for periods longer than 60 years.

The changes of river discharge regimes can be analysed not only as linear, but also as periodic processes. Discharge regime of both the largest rivers and medium sized rivers in Latvia do have well expressed periodicity of high and low water periods (Figs. 4, 5).

In order to characterize periodicity and estimate major periods of river discharge changes, periodograms (Pekarova *et al.* 2003) were calculated using spectral analysis (Fig. 6). Using this approach, statistically significant periods in the annual river discharge in the Baltic region could be identified for periods of 38, 28, 14, 19, 5, 4, 3 years as being significant.

The general patterns of the periodicity of water flow regime in several major rivers in Latvia are summarised in Table 2. For the last 100–125 years low discharge periods for rivers of Latvia are longer than high discharge periods, and they last from a minimum of 10 years up to a maximum of 21–27 years. Historically high discharge periods used to last from 10 years (6–8 years), however, for the past 30 years for the biggest rivers (except River Lielupe) the duration could be observed to reach 20 to 27 years. Similar periodicity of river discharge changes has been found in the study of Goudie (1992) for river discharge in Eastern Europe and similar short-term fluctuations with mean duration of 4–6 years have been found in Estonia and

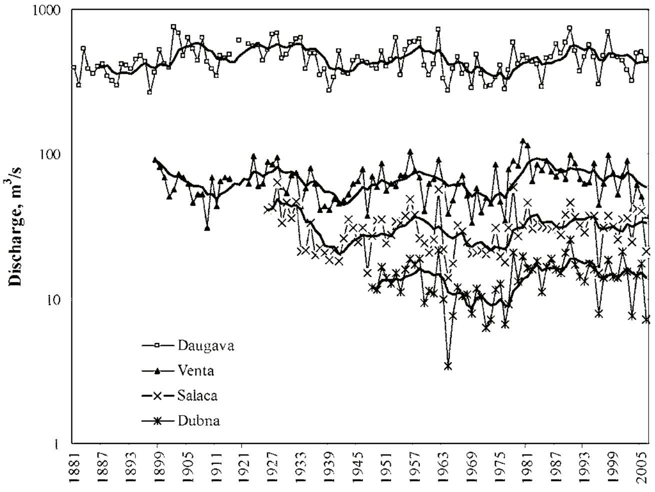

Fig. 4. Long–term changes of river discharge in Latvia (large and middle–sized rivers; yearly and ten–year moving average).

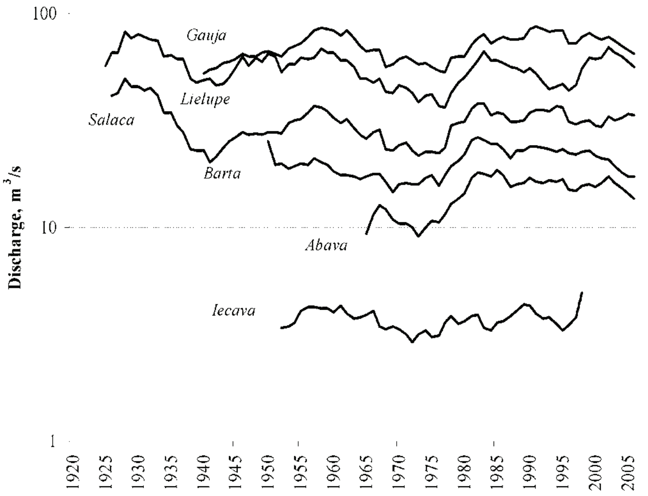

Fig. 5. Long-term changes of river discharge in Latvia (middle–sized and small rivers; yearly and ten–year moving average).

Table 2. Changes of low and high discharge periods for the largest rivers in Latvia.

Low discharge period	Years	$Q_{mean,}$ m^3/s	K	High discharge period	Years	$Q_{mean,}$ m^3/s	K
Daugava (1881–2006)							
1881-1901	21	401	0.87	1902-1908	7	595	1.29
1909-1921	13	442	0.96	1922-1936	15	549	1.19
1937-1952	16	419	0.90	1953-1958	6	555	1.20
1959-1985	27	401	0.87	1986-2000	19	490	1.06
2001-2006	6	431	0.93				
Total, mean	*83*	*419*	*0.91*		*43*	*552*	*1.19*
Venta (1897–2006)							
1900-1923	24	60.2	0.92	1924-1930	7	72.1	1.10
1931-1949	19	57.0	0.87	1950-1959	10	69.9	1.07
1960-1977	18	57.1	0.88	1978-2002	25	79.1	1.21
2003-2006	4	48.1	0.74				
Total, mean	*65*	*55.6*	*0.85*		*42*	*73.7*	*1.13*
Salaca (1927–2006)							
				1927-1932	6	44.9	1.48
1933-1952	20	25.6	0.84	1953-1962	10	34.6	1.14
1963-1976	14	22.4	0.74	1977-2005	29	33.9	1.11
Total, mean	*34*	*24.0*	*0.79*		*45*	*37.9*	*1.25*
Gauja (1940–2006)							
1940-1952	13	62.5	0.89	1953-1962	10	84.5	1.21
1963-1977	15	55.8	0.80	1978-2005	28	77.3	1.10
Total, mean	*28*	*59.2*	*0.84*		*38*	*80.9*	*1.15*
Lielupe (1921–2006)							
				1921-1932	12	71.9	1.29
1933-1942	10	49.4	0.89	1943-1962	20	61.8	1.11
1963-1977	15	39.8	0.72	1978-1983	6	66.3	1.19
1984-1997	14	48.9	0.88	1998-2005	8	65.7	1.17
Total, mean	*39*	*46.0*	*0.83*		*46*	*66.4*	*1.19*

Finland (Hiltunen 1994). Periodicity of river discharge changes has been stressed in studies of river discharges in Central Europe (Pekarova *et al.* 2003).

The use of integral curves allows a better identification of oscillation patterns. Fig. 7 shows integral curves for water discharges in the five largest rivers in Latvia, but Fig. 8 the same for the major rivers in the Baltic region and Finland. Differences are seen between Lielupe and the other four rivers in Latvia, and for all rivers there is an apparent difference between observations before and after 1920. For example, in the River Lielupe, water discharge decreased from 1986 to 2000, in contrast to the other rivers that showed a stable increasing tendency. As it can be seen from Fig. 8, in year 1996, the water discharge reached the lowest value during the last ten years for rivers in Latvia. The differences in flow patterns between the River Lielupe and other rivers in Latvia can be explained also by bearing in mind, that the gauging station in Lielupe, which is situated considerably more upstream (110 km) and thus can reflect slightly more than 50 % of the total river discharges. The Lielupe River basin is moderately affected by melioration and by construction of various hydrotechnical constructions (dams, ponds etc.). Also agricultural activities influence the water flow regime in this river.

The use of integral curves for studying river discharge changes for the major rivers in the Baltic region

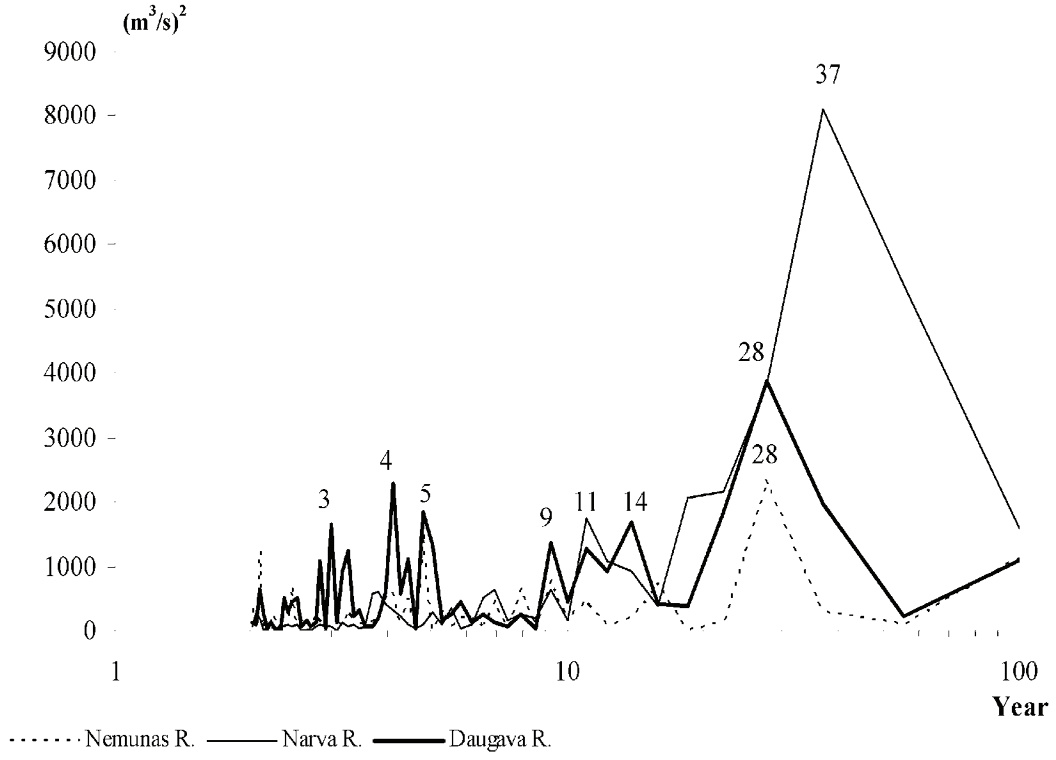

Fig. 6. Periodogram of annual river discharge time series for the rivers in the Baltic region.

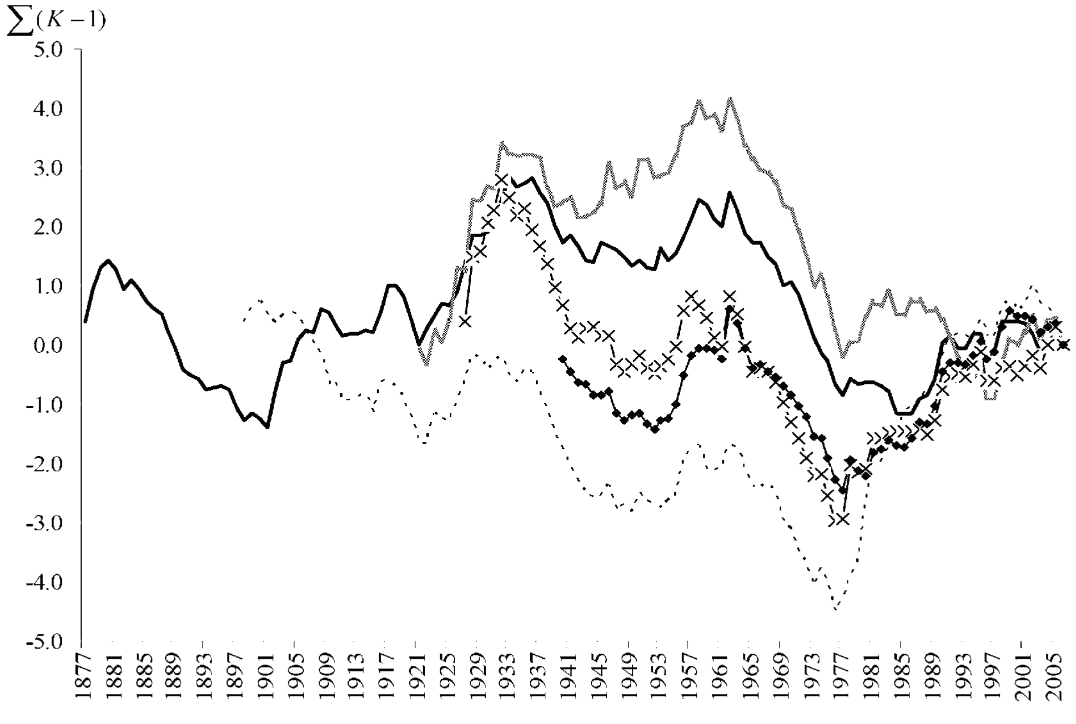

Fig. 7. Normalized integral curves for coefficients of the annual runoffs of rivers in Latvia.

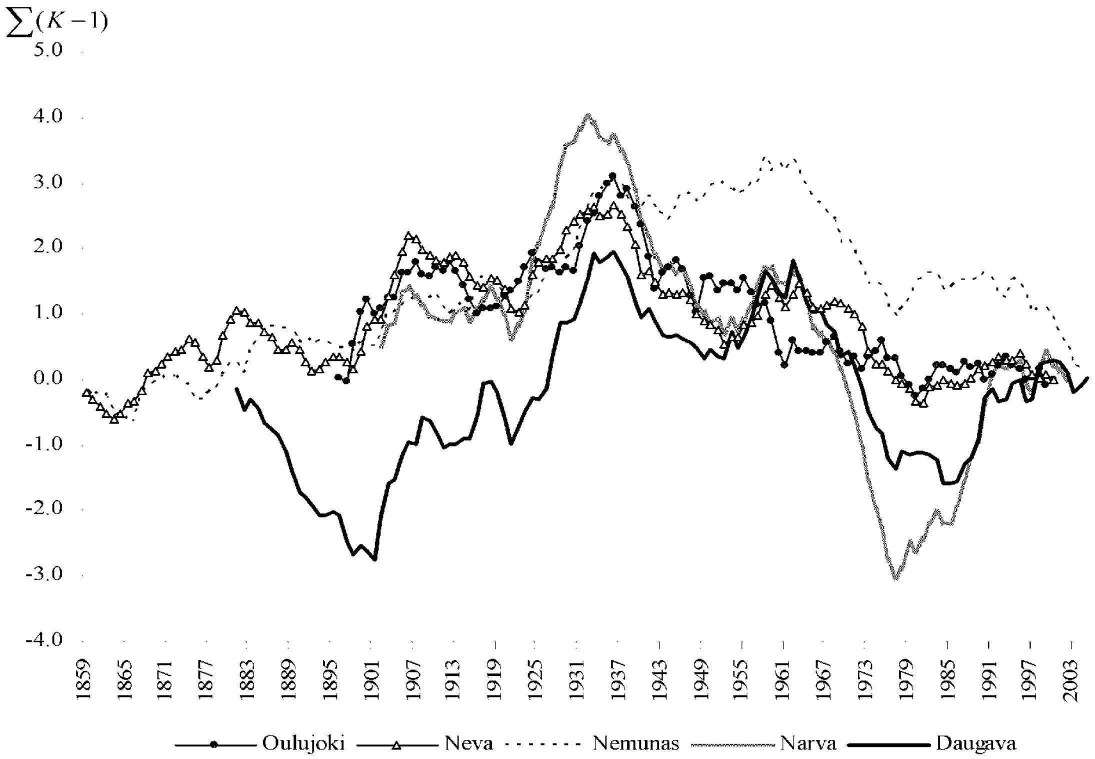

Fig. 8. Normalized integral curves for coefficients of the annual runoffs of rivers in Baltic Sea region.

and Finland shows a significantly differing pattern depending on the placement in the northern-southern gradient. The differences are highest if comparing the most southern (Nemunas River) and the most northern (Oulujoki River) with the other studied rivers forming an intermediate position.

The trend analysis of maximal and minimal discharges (Fig. 9) indicates statistically significant trend of decrease of maximal discharges (except for River Salaca) and increase of minimal discharges (except for River Gauja). Also analysing long term changes of maximal and minimal discharges for River Daugava (Fig. 10), the same pattern becomes evident: there it can be observed decrease for maximal discharges, but the years with maximal discharges have not been observed during last 50 years and the maximal discharge

Table 3. Number of years with recorded extremely high yearly discharge (probability ≤ 10 %) on major rivers in Latvia starting with regular hydrological observations for years up to 2006.

Period of observations	Daugava (Daugavpils)	Lielupe (Mežotne)	Salaca (Lagaste)	Gauja (Sigulda)	Venta (Kuldīga)
	1881–2006	1921–2006	1926–2006	1940–2006	1898–2006
1922–1936 (high discharge)	4	3	4	0	1
1951–1962 (high discharge)	5	4	3	6	3
1979–2006 (high discharge)	0	0	0	0	0
Other years (case)	4 (1896, 1900, 1917, 1941)	3 (1940, 1941, 1946)	1 (1968)	1 (1945)	8 (1899-1901, 1914, 1915, 1940, 1948)
Total	13	11	8	7	12

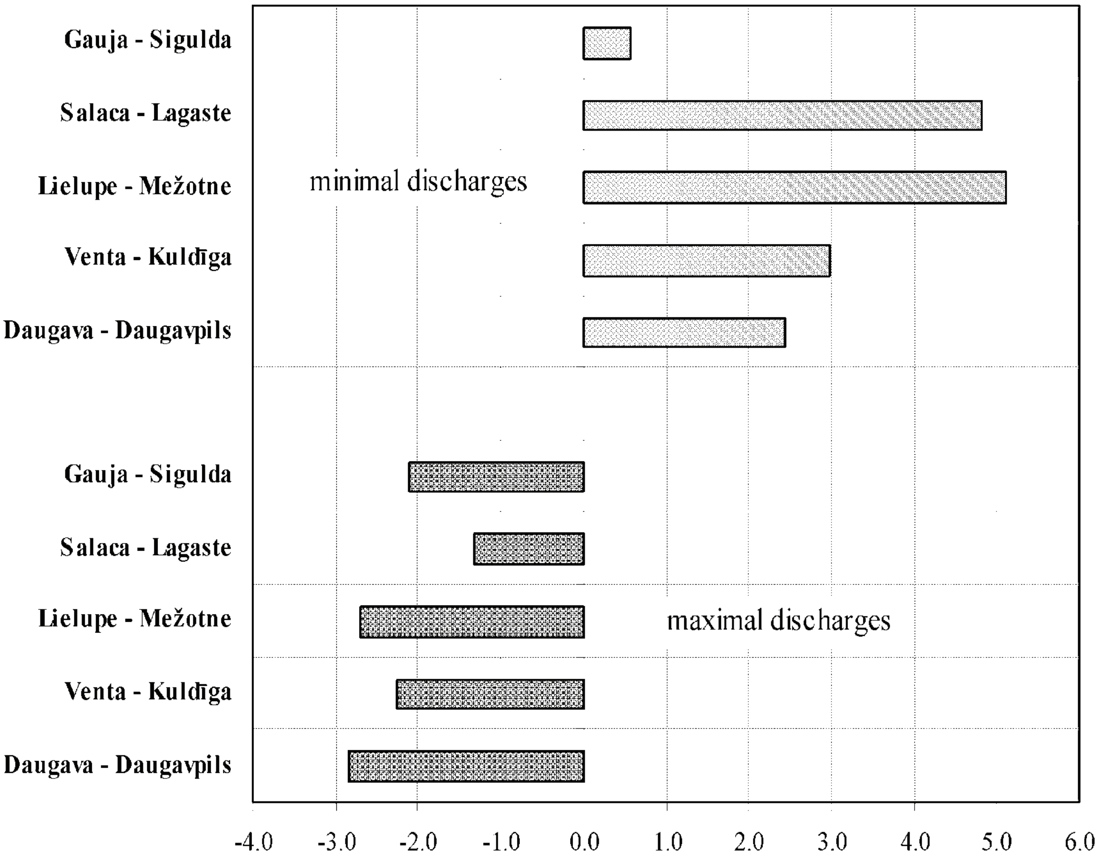

Fig. 9. The long–term trend (1904–2004) of monthly (30 days average) water runoffs for rivers of Latvia after Mann–Kendall test criteria.

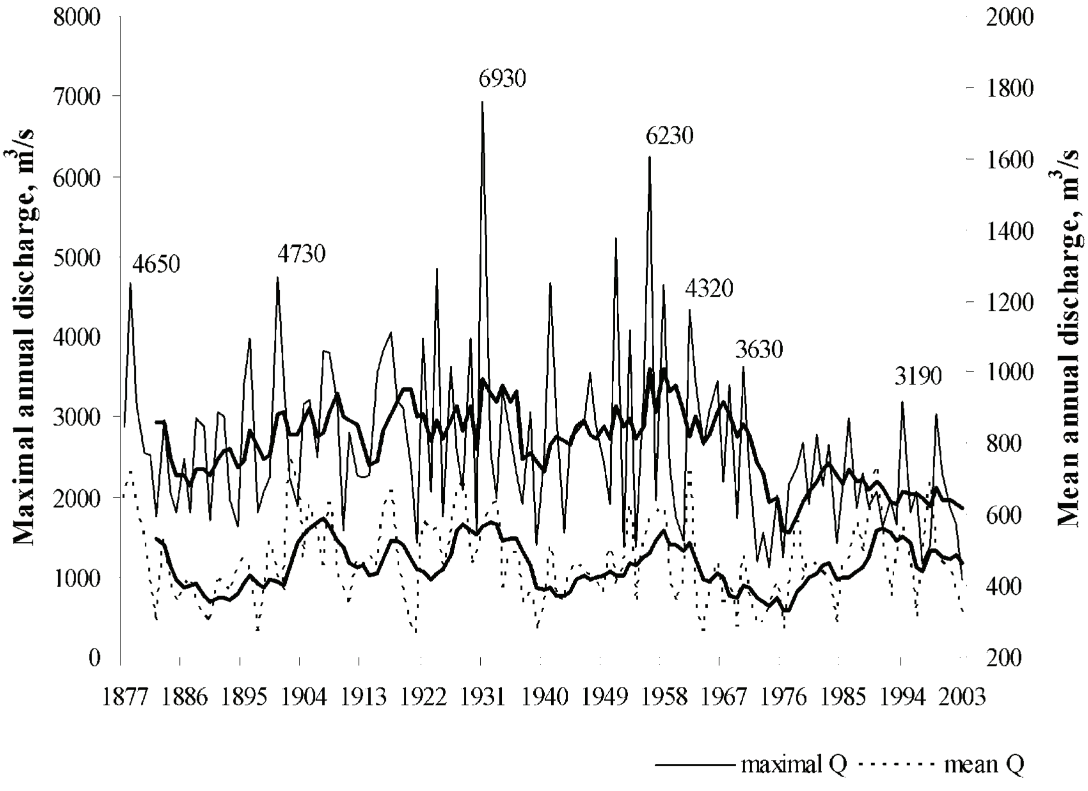

Fig. 10. Changes for last 130 years of an extreme and average annual runoff of the River Daugava at gauging station Daugavpils. Data was smoothed with a six–year moving average.

level has been the lowest for all the observation period. The same findings support also analysis of extreme yearly discharges for major rivers of Latvia. As it can be seen from Table 3, during last decades virtually no years with extremely high river discharges have been observed.

CONCLUSIONS

River discharge regimes in the Baltic countries during last century, as shown by the example of Latvia, have been subjected to major changes – highly possibly attributable to the climate change, but also changes of land-use patterns and development of hydro technical buildings could have affected the river regime. At the same time, well-marked regular changes of high water and low water periods have been observed. Spectral analysis shows that statistically significant periods in the annual river discharge in the Baltic region could be identified for periods of 38, 28, 14, 19, 5, 4, 3 years. Periodic long-term processes do have significant impact also on the character on changes of maximal and minimal discharges for the studied rivers and major recent decrease of the maximal discharge level and reduction of extreme yearly discharges.

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