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The variability of long–term runoff series in the Baltic Sea drainage basin

Brunonas Gailiušis, Jūratė Kriaučiūnienė, Darius Jakimavičius, Diana Šarauskienė

The article is dedicated to the 200-year anniversary of the hydrological survey of the Nemunas River

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Abstract Studying the variability of long–term runoff series is important in order to learn about the effects of climate change and human activity. The results of such analyses depend on the availability of long–term data. Long–term runoff data variability (annual, highest and lowest monthly discharge) was investigated in five rivers (the Nemunas, Neva, Oder, Vistula and Luleaelven) of the Baltic Sea drainage basin. These rivers have long–duration data. The discharge time series in the Nemunas at Smalininkai are the oldest data (1812–2009) and are related to the runoff in Europe and the Baltic Sea region as well. The other investigated rivers have discharge time series longer than one century. Long–term variability of annual discharge (the dry and wet phases of water flow) are common in the Nemunas, Neva, Vistula and Oder. One dry or wet phase continues for about 13–13.5 years and the whole period of variability is 26–27 years. The changes in the highest and lowest monthly discharges for the major rivers in the Baltic Sea drainage basin have been studied using the analysis of trends and anomalies expressed by percent from the reference period. Similar variability in the river runoff was found in the Nemunas, Neva, Vistula and Oder.

Keywords *Discharge, long term variability, trends, Baltic Sea drainage basin.*

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INTRODUCTION

The analysis of changes of river runoff is very important in order to learn about the effects of climate variability and human activity. The results of this analysis depend on the availability of long–term data series. Systematic measurements of runoff in the European rivers started two centuries ago. The longest time series of the river discharge are available in the Goeta River (data from 1807), Nemunas[1] (1811), Dnieper (1818), Weser (1821), Danube (1840), Wuoksi (1847), Elbe (1851), Neva (1859) and Loire (1863) (Pekarova *et al.* 2006). The Swedish have the longest time series in Europe. The Goeta River outflows from the lake Vaenern and the water gauging station (WGS) are at the outlet of the lake. Therefore, the data of this WGS reflects the influence of the lake on the hydrological regime of the Goeta River.

The long–term discharge time series at Smalininkai in the Nemunas (Fig. 1) are the oldest data related to the runoff of a big river (catchment's area at Smalininkai is 81 200 km²). In 2011 the Lithuanian hydrologists are going to celebrate the 200 year anniversary of hydrological investigations in the Nemunas River. The first stationary hydrological measurements in Lithuanian rivers were made in 1810. In the beginning of the 19th century, the four water gauging stations (WGS): Old

1 Nemunas (in Lithuanian), Neman (in English), Неман (in Russian).

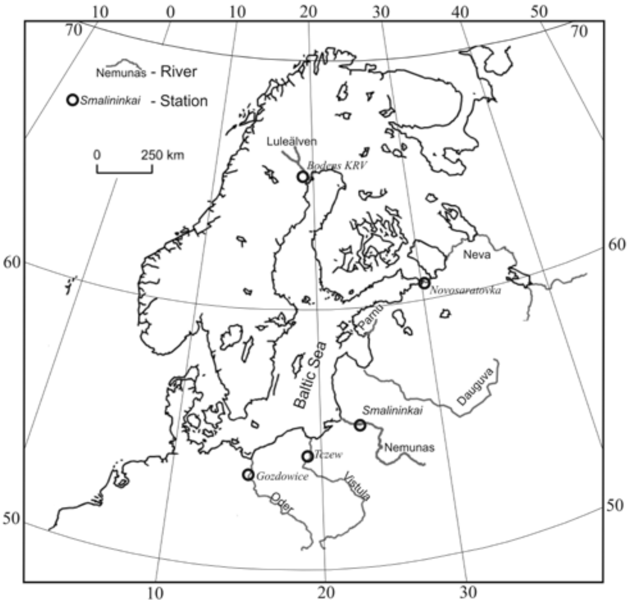

Fig. 1. The map of analyzed rivers and the measurement sites. Compiled by D. Jakimavičius.

Sėliai (26 07 1810), Rusnė (22 08 1810), Tilžė (01 01 1811) and Smalininkai (01 10 1811) were established on the Nemunas River. Although Smalininkai WGS was set up the last, it is considered as the first water gauging station established in Lithuania. The remaining three WGS were on the left bank of the Nemunas that currently does not belong to the Lithuanian territory. The main historical events of hydrological survey of the Nemunas River are described in Table 1 (Kolupaila 1930; Kolupaila 1934; Macevičius 1970).

Table 1. The main events of the Nemunas River investigation history.

Date	Historical events/facts
1811	Establishment of Smalininkai WGS
1812	Beginning of systematic measurements with stable rod
1845	Measurement of the first discharge
1864–1866	Comprehensive hydrometric works in the mouth of the Nemunas
1876–1877	Establishment of fifteen WGS in the middle and the upper part of the Nemunas
1874–1892	Regulation of the Nemunas part between Smalininkai and the Curonian Lagoon
1922–1931	Measurement of 640 discharges in the Nemunas River

The Head of Hydrometric Party S. Kolupaila[2] (Fig. 2) was interested in the data of Smalininkai WGS very much. Till 1890 only water level was measured at Smalininkai, therefore S. Kolupaila estimated the Nemunas runoff for the period of 1812–1932, using discharge curve and introducing corrections due to the systematic rise of the river bed (Kolupaila 1932). In 1960, the mean annual, minimum and maximal discharges of the Nemunas River were published for the period of 1812–1955 (Lasinskas, Burneikis 1960). These data enable the Lithuanian and foreign scientists to perform many hydrological investigations.

The changes of river discharge time-series (trends and long–term variability) have been extensively studied worldwide. Long–term trends and cyclicity in discharge time series of 18 major European rivers were identified during the period of 1850–1997 (Pekarova *et al.* 2006). The statistical analysis of these series did not confirm any long–term increase or decrease in discharge during the last 150 years. Dry cycles of 13.5 and 28–29 years were identified in the European rivers.

There are many studies on the river discharge changes and variability in Northern Europe (Lindström, Alexandersson 2004; Roald *et al.* 1997; Vehviläinen, Huttunen 1997; Thodsen 2007; Hisdal *et al.* 2003). Long–term variations in runoff and occurrence of floods are analyzed in Sweden (Lindström, Bergstrom 2004). The average runoff from all rivers of Sweden increased by 5% over the past century, but the trend was not statistically significant.

Fig. 2. Prof. Steponas Kolupaila. Courtessy of the Science and Encyclopaedia Publishing Centre, Vilnius.

The changes in river discharge of the Baltic States were investigated according to the common methodology (Klavins *et al.* 2008; Reihan *et al.* 2007). Increasing tendency in winter discharge was determined for all three investigated periods (1923–2003, 1941–2003, and 1961–2003). No trend was observed for the spring, summer and autumn seasonal stream–flow in most of the rivers in the Baltic States (Reihan *et al.* 2007). Well marked regular changes of high water and low water periods have been observed in the annual river discharge in the Baltic region (Klavins *et al.* 2008).

2 Prof. Steponas Kolupaila (14 09 1892 – 09 04 1964) was the author of the first handbook "Hydrometry", published in Russian in 1918. He was a patriarch of Lithuanian river hydrology, professor (1926), doctor of Engineering (1940), a member of Lithuanian Academy of Sciences (1941), professor of Notre Dame University in the United States (1948-1963).

The Baltic Sea drainage basin is the region where variations of hydrological parameters are well investigated (Hisdal *et al.* 2007; Lindström *et al.* 2006). However, many scientists addressed their researches to the changes of the river runoff in the individual country or group of countries, but the analysis of long–term runoff series, especially of the largest rivers of the Baltic Sea drainage basin, has not been carried out yet.

The aim of this paper is to analyze variability of long–term runoff time series in the Baltic Sea drainage basin and to determine the tendencies of this variability. The runoff data series were obtained from the Global Runoff Data Centre in Koblenz, Germany, and from Lithuanian Hydrometeorological Service.

OBJECT OF INVESTIGATIONS

Hydrological settings of the investigated rivers

Nine countries share the shoreline of the Baltic Sea and its drainage basin includes territories from altogether fourteen countries. The size of the total area is approximately 1 729 000 km^2 (Wulff *et al.* 2001). The five largest rivers in descending order are the Neva, Vistula, Daugava, Nemunas, and Oder (Table 2). As can be seen from the table, the specific runoff is highly variable in the main river basins.

Only seven rivers (marked **bold**, Table 2) have long observation data series. Since the Goeta River inflow to Kattegat and its belonging to the Baltic Sea are negotiable, it was not added to the studied river group. The Dauguva River has long–term data series, but these data are not available in the database of the Global Runoff Data Centre. Therefore, five rivers were selected for the further analysis (Fig. 1).

Many rivers in the Baltic Sea drainage basin are affected by regulation. This is particularly pronounced in Sweden, where hydroelectric power covers about a half of the demand for electricity. The development of hydropower leads to a more artificial hydrograph, where most of the flow–peaks are stored in the reservoirs and the winter base–flow is increased (Wulff *et al.* 2001). The most important river for hydropower production in the Nordic countries is the **Luleaelven**, which flows south–east from the Scandinavian Mountains to the north–western part of the Bothnian Bay. The Luleaelven is a major river in Sweden, rising in northern Sweden and flowing southeast for 460 km before reaching the Gulf of Bothnia at Lulea. Its runoff was especially affected by high regulation after 1968 (Carlsson, Sanner 1995). The Luleaelven River has large numbers of hydropower stations in series along the river. In this river the total length of the regulated reaches is about 670 km, approximately 146 km of which constitute the reservoirs (Svensson 2000).

The **Neva** is a river that drains Lake Ladoga (the largest lake in the European part of Russia). The Neva River is short (74 km), but has the largest mean annual runoff in the Baltic Sea drainage area. The Neva banks contain four cities: Saint Petersburg, Shlisselburg, Kirovsk and Otradnoye, as well as dozens of settlements. The river is navigable throughout and is part of the Volga–Baltic Waterway and White Sea – Baltic Canal. Lake Ladoga accumulates large volumes of water, regulates and smoothes the Neva runoff. In the area of Neva basin, rainfall greatly exceeds evaporation; the latter accounts for only 37.7% of the water consumption from the Neva and the remaining 62.3% are water runoff (Leningrad. Historical atlas 1981).

The **Vistula** River**,** flowing entirely on the territory of Poland, is the longest river draining to the Baltic Sea at 1024 km in length. The Vistula flows north from its source on the Barania Góra in the Beskidy Mountains in the Carpathian range to its mouth in the Baltic Sea. The Vistula basin is divided into three regions with distinctly different river flow regimes: the highland-dominated Upper Vistula basin from the source downstream to the San confluence; the Middle Vistula from the San to the Narew confluence; and the Lower Vistula. The annual rainfall in the Vistula basin is about 600 mm, with a summer maximum (Cyberski *et al.* 2006). The Vistula is a river with high and frequent summer floods triggered by continuous rainfall

Table 2. The ten largest rivers of the Baltic Sea system, Danish Sounds and Kattegat, their approximate drainage area, mean annual and specific runoff during 1950–1990.

River	Drainage area (km^2)	Mean annual runoff (m^3/s)	Specific runoff (l/(s·km^2))
Neva (Нева)	281 000	2460	8.8
Vistula (Wisła)	194 400	1065	5.5
Daugava	87 900	659	7.5
Nemunas	98 200	632	6.4
Oder (Odra)	118 900	573	4.8
Kemijoki	51 400	562	11.0
Goeta (Göta älv)	50 100	574	11.5
Aengermanaelven (Ängermanälven)	31 900	489	15.0
Luleaelven (Lule älv, Luleälven)	25 200	486	19.0
Indalsaelven (Indalsälven)	26 700	443	16.5

in the Carpathians and their foreland. Spring floods, which occur regularly, predominate, while summer and winter floods are less frequent (Lajczak *et al.* 2006). The diversity of channelization works was undertaken in the second half of the 20th century, combined with the setting up of reservoirs and dams on the Vistula and its tributaries.

The **Oder** River is the second largest river in Poland after the Vistula. Its source is in the Sudety Mountains in the Czech Republic. In its upstream course, the Oder River has the features of a highland river, while in the middle and downstream course, the river flows through lowlands into the Baltic Sea (Kundzewicz 2002). Vegetation in its drainage basin is characterized by forests in the southernmost mountainous region, where precipitation may exceed 1000 mm, and agricultural grassland for most of the remaining part. The annual precipitation in the predominant lowland reaches 550 mm. The discharge maxima occur in spring from the combination of rainfall and snowmelt. Occasionally in summer extreme rainfall may cause extreme stream–flow as well (Mengelkamp *et al.* 2001). The river is an important waterway, navigable throughout most of its length. It forms a link, by way of the Gliwice Canal, between the great industrialized areas of Silesia (Śląsk), in south–western Poland, and the trade routes of the Baltic Sea and beyond. The Oder is connected with the Vistula by means of a water route utilizing the Warta and Noteć rivers.

The **Nemunas** is a major Lithuanian river. The total length of the Nemunas is 937 km. The drainage basin of the Nemunas has an area of 98 200 km^2, 46 600 km^2 of which is in Lithuania (i.e. 72% of Lithuanian territory). The Nemunas rises in Belarus, 45 km southwest from Minsk. On the average, 21.8 km^3 of this river water flows to the Baltic Sea (through the Curonian Lagoon) during a year. The river consists of three parts: the Upper Nemunas begins at the source and ends 402 km down at the confluence with the Katra; the Middle Nemunas is 327 km long and ends at the confluence with the Neris; the Lower Nemunas is the shortest – 208 km. The Nemunas delta begins 48 km from the river mouth. The mean discharge of the river at Smalininkai is 535 m^3/s. The seasonal river runoff distribution is the following: 38 % of annual runoff belongs to spring, 16 % to summer, 20 % to autumn and 26 % to winter season (Jakimavičius, Kovalenkovienė 2010). The mean annual precipitation in the Nemunas basin is 700 mm. The hydrological regime of the Nemunas River was irreversibly changed after construction of Kaunas Hydropower Station and Kruonis Hydroelectric Pumped Storage Plant.

DATA AND METHODS

The rivers, that directly inflow into the Baltic Sea and have data series of at least 90 years long were selected for the study (Fig. 1). The main data of the selected rivers (gauging stations, dates of observation, mean discharges and specific runoff of the studied period) are presented in Table 3.

The runoff data of the rivers (Luleaelven, Neva, Oder, Vistula and Nemunas) used in this study has been received from Global Runoff Data Centre in Koblenz (Global Runoff Data Centre 2009). The newest data of the Nemunas river runoff (1990–2009) were obtained from the archive of Lithuanian Hydrometeorological Service (Lithuanian Hydrometeorological Service 1990–2009).

Table 3. General information relating to the water measurement stations at the selected rivers.

River	Station	Time series (No. of years)	Catchment area, km^2	Mean Q, m^3/s	q, l/(s km^2)
Luleaelven	Bodens KRV	1900–2003 (104)	24 924	500.5	20.08
Nemunas	Smalininkai	1812–2009 (198)	81 200	534.8	6.59
Neva	Novosaratovka	1859–1988 (130)	281 000	2511.4	8.94
Oder	Gozdowice	1900–1994 (95)	109 729	530.4	4.83
Vistula	Tczew	1900–1994 (95)	194 376	1042.1	5.36

The analysis of long–term variability of river runoff was performed using the following data of hydrological stations: mean annual discharge, the highest and lowest monthly discharges, and numbers of months when the highest or lowest monthly discharges were fixed.

Variability of long–term runoff series in the Baltic Sea drainage basin was analyzed using anomalies of the annual, highest and lowest monthly river discharges, integrated curves of annual discharges and the results of the Mann-Kendall test. The anomalies of discharges Q (expressed in %) were calculated by division of long–term series with mean values of the reference period (1961-1990). WMO (1988) defines the latest global standard period of 30 years in 1961–1990, therefore the reference period was selected the same. The analysis of the integrated curves of annual runoff is used to describe the periods of different water availability. The method of integrated curves is used for the analysis of runoff variability. The integrated curve ($\sum_{i=1}^{n}(k_i-1)$) is the sum of variations of modular coefficients from the average value. Modular coefficient is $K_i = Q_i / \bar{Q}$ where Q_i – discharge in year i, $\overline{Q}$ – mean discharge for the entire period of observation. The integrated curves point up the dry and wet periods of rivers runoff.

Table 4. Correlation coefficients of annual discharge time series in 1901–1988.

River	Oder	Vistula	Nemunas	Neva	Luleaelven
Oder	1	0.67	0.25	-0.16	-0.27
Vistula		1	0.450	-0.12	-0.22
Nemunas			1	0.33	-0.05
Neva				1	0.11
Luleaelven					1

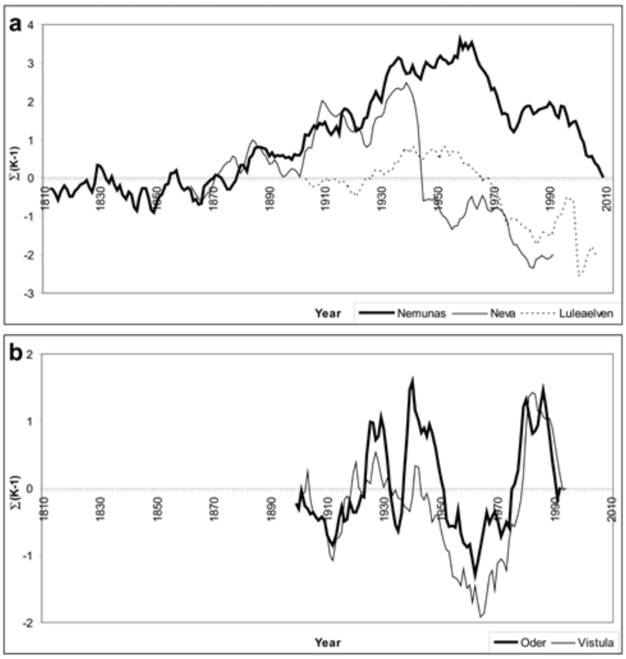

Fig. 3. Integral curves of the annual river discharge: a) the Nemunas, Neva and Luleaelven rivers, b) the Oder and Vistula rivers. Compiled by J. Kriaučiūnienė.

The Mann-Kendall test (the details of the theory see in Salas 1993) searches for trends in time series of Q without specifying whether the trends are linear or non-linear. The WMO (WMO 1988) recommends non-parametric Mann-Kendall test with a 5% significance level.

RESULTS

The five selected rivers from the Baltic Sea drainage basin are from the different geographical regions and their runoff formation depends on particular hydrometeorological conditions and anthropogenic activity. Correlation analysis of the annual discharge series was performed (Table 4) with the intention to find the best correspondence between the rivers. The best correlation is found between the Oder and Vistula, also between the Nemunas and Neva. However, no satisfactory correlation was determined between the Luleaelven and the remaining rivers by reason of the significant regulation of this river.

The changes of annual discharges of the rivers are evaluated by the analysis of the long–term cyclical variability and trends. The period of long–term variability consists of wet (K>1) and dry (K<1) phases. One cyclical period has one wet and one dry phase. Integral curves of the annual discharges show the periods of long–term variability (increasing part of curve corresponds to the wet phase, and decreasing part to the dry phase). Long–term variability in the annual discharge series was determined for all rivers (Fig. 3). The Nemunas and Neva, as well as the Oder and Vistula, have similar cyclical variability of discharge. In all studied rivers, one wet or dry phase continues for about 13–13.5 years and the whole period of one cycle (wet phase plus dry phase) for 26–27 years (Table 5). It was rather complicated to single out the mentioned phases in the Luleaelven, because it has different hydrological regime than the other studied rivers. The Luleaelven River is highly regulated and has an entire dam cascade on it; therefore, this river is the least natural and the most affected by anthropogenic activities.

The trend analysis enables evaluating the general tendencies of changes of the river discharges. Two time periods of data were selected: the longest avail-

Table 5. Dry (K<1) and wet (K>1) phases of long–term variability in the annual discharge time series of the rivers of the Baltic Sea drainage basin.

Nemunas		Neva		Oder		Vistula	
Period	K (number of years)	Period	K (number of years)	Period	K (number of years)	Period	K (number of years)
1812-1815*	0,86 (4)	–	–	–	–	–	–
1816–1829	1,07 (14)	–	–	–	–	–	–
1830–1843	0,91 (14)	–	–	–	–	–	–
1844–1857	1,08 (14)	–	–	–	–	–	–
1858–1866	0,90 (9)	1859–1866*	0,98 (8)	–	–	–	–
1867–1885	1,08 (19)	1867–1881	1,09 (15)	–	–	–	–
1886–1898	0,98 (13)	1882–1898	0,94 (17)	–	–	–	–
1899–1910	1,08 (12)	1899–1913	1,11 (15)	1901–1913	0,94 (13)	1901–1912	0,91 (12)
1911–1921	0,98 (11)	1914–1923	0,92 (10)	1914–1927	1,13 (14)	1913–1927	1,11 (15)
1922–1936	1,13 (15)	1924–1936	1,12 (13)	1928–1937	0,84 (10)	1928–1939	0,93 (12)
1937–1948	0,98 (12)	1937–1952	0,76 (16)	1938–1948	1,14 (11)	1940–1948	1,01 (9)
1949–1962	1,05 (14)	1953–1963	1,08 (11)	1949–1964	0,86 (16)	1949–1964	0,91 (16)
1963–1977	0,85 (15)	1964–1980	0,89 (17)	1965–1981	1,15 (17)	1965–1982	1,19 (18)
1978–1990	1,06 (13)	1981–1988*	1,04 (8)	1982–1994	0,91 (13)	1983–1994	0,88 (12)
1991–2009	0,90 (19)	–	–	–	–	–	–

* – not full period.

able period from all WGS data (1901–1990) and the reference period (1961–1990). The long–term trends (1901–1990) of annual discharge were not significant for all investigated rivers (Table 6). A significant increase in annual flow occurred during the reference period (1961–1990) in the Nemunas and Luleaelven where no trend was found in the annual discharge of the remaining rivers. The trend of the longest time series of annual discharge of the Nemunas (1812–2009) was insignificant.

Long–term anomalies of annual discharge indicate the difference (expressed by %) between the discharges of a particular year and the mean discharge in the reference period (1961-1990). The changes of anomalies of long–term series of annual discharge are almost synchronic in the Nemunas and Neva (Fig. 4a) and in the Oder and Vistula (Fig. 4b).

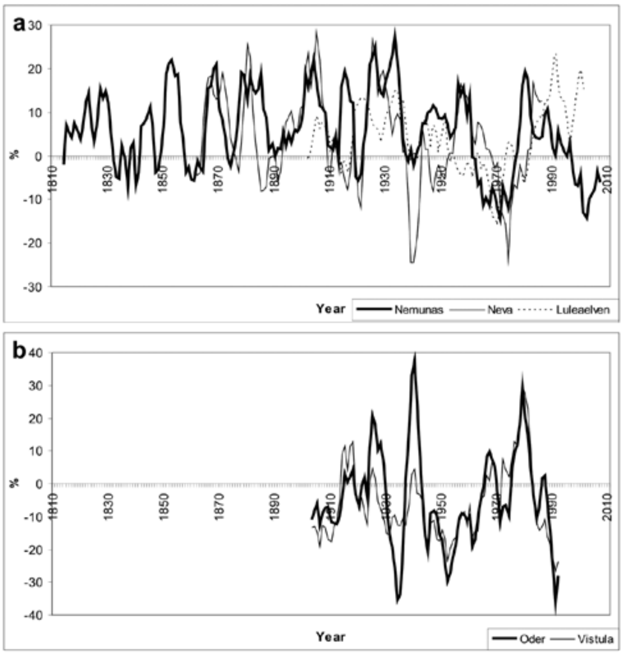

Fig. 4. Long–term anomalies (%) of the annual discharge from the reference period of 1961–1990: a) the Nemunas, Neva and Luleaelven rivers, b) the Oder and Vistula rivers. Compiled by D. Jakimavičius, D. Šarauskienė.

Table 6. Mann-Kendall test statistics of annual, highest and lowest monthly water discharge for rivers in the Baltic Sea drainage basin in 1901–1990 and 1961–1990 (statistic is marked in bold if the trend is statistically significant at the 5 % (or less) level).

River	Mean annual discharge		Highest monthly discharges		Lowest monthly discharges	
	1901–1990	1961–1990	1901–1990	1961–1990	1901–1990	1961–1990
Nemunas	-1.71	**2.32**	**-2.73**	-0.25	1.44	**3.57**
Neva*	-1.58	1.01	-1.46	0.81	**-2.61**	-0.14
Vistula	0.79	-0.37	-0.70	-1.94	**3.46**	0.80
Oder	0.62	0.12	-1.15	-0.04	**2.82**	0.29
Luleaelven	-1.50	**1.96**	**-8.00**	-0.82	**9.59**	**2.91**

* - data of the Neva River are available to 1988.

The biggest anomalies in annual discharge variation were estimated in the Oder (±40%). The anomalies of annual discharges in the Vistula are slightly less, but the long–term variations of anomalies in the Vistula and Oder are almost synchronic. Positive anomalies of the annual discharges (in average about 8%) were identified in the Nemunas during the period of 1812–1960, whereas in the later period (1961–2009), negative anomalies (on the average of about -2%) were determined. The reason of such changes of anomalies could be a very dry runoff phase in the Nemunas in 1963–1977.

In hydrological studies it is very important to know not only the variability of annual runoff, but also the variability of runoff extreme parameters. The trend analysis of the *highest monthly discharges* (Table 5) shows a significant negative trend in the Nemunas and Luleaelven rivers for the long–term period (1901–1990). The largest floods in the Nemunas River were in 1958, 1941 and 1926; furthermore, there were no big floods from 1970. This is the reason why the long–term trend of the Nemunas *highest monthly discharges is significantly negative. Dam cascade regulated the runoff of the* Luleaelven. Many of the dams were installed during the sixth-seventh decades of the 20th century. This anthropogenic activity decreased the flood peaks in the river. In the remaining studied rivers, there was no trend for the long period. The Nordic results showed no systematic trends in the long–term flood time-series (Hisdal *et al.* 2003). In the case of the reference period 1961–1990, there were no significant trends in time series of the highest monthly discharges of all rivers.

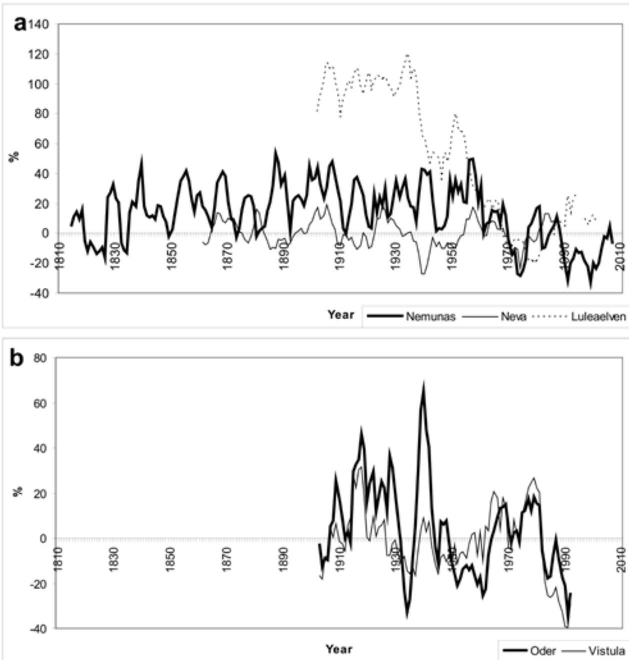

Fig. 5. Long–term anomalies (5-year moving average) of the *highest monthly discharge* from the reference period of 1961–1990 (%): a) the Nemunas, Neva and Luleaelven rivers, b) the Oder and Vistula rivers. Compiled by D. Jakimavičius, D. Šarauskienė.

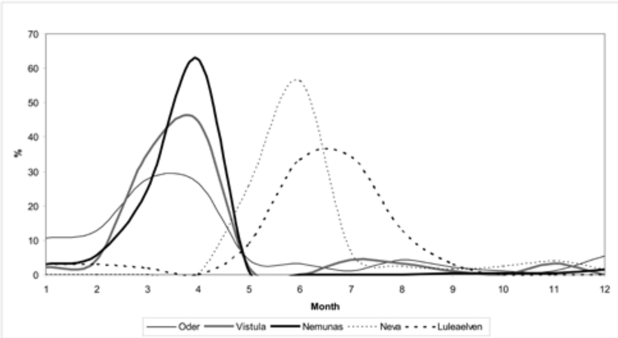

Fig. 6. Percentage distribution of the months when the highest monthly discharges were detected in the rivers. Compiled by D. Jakimavičius, J. Kriaučiūnienė.

The long–term anomalies of the highest monthly discharge in the rivers are shown in Fig. 5. Positive anomalies (to 60%) dominated in the highest monthly discharge of the Nemunas in the long–term period of 1812–1960. A big reservoir was installed in the Nemunas at Kaunas and the Kaunas Hydropower Station began its activity in 1960. The river runoff regulation by this power station saved the lower part of the Nemunas from dangerous floods and decreased the maximal discharges in the period of 1961–2009. The anomalies of the highest monthly discharge in the Neva River are less than in the Nemunas (Fig 5a). Very high anomalies (to 120%) were found in the Luleaelven discharge in the beginning of the long–term period. The river was especially affected by high regulation after 1968 and the anomalies of the highest monthly discharge decreased the most from this year. The anomalies of the Vistula and Oder were almost synchronic (Fig. 5b), except the anomalies of the Oder River in 1940–1941.

In the analysis of runoff discharge distribution, determination of the date (month) of the maximal discharges is of great importance. The analysis of dates allows evaluating changes in river runoff distribution during a year. Snowmelt water forms a significant part of the annual runoff. Snow melting is closely linked to air temperature (Zveryaev 2007). Therefore, spring floods, originated from snowmelt water, start earlier in southern river basins and later in the northern basins. Figure 6 confirms such assumption. In the Oder, Vistula and Nemunas the highest monthly discharges are observed the earliest (in March-April). Slightly later spring floods begin in the Neva River basin (in May-June). The latest floods are in the Luleaelven (in June-July).

The analysis of long–term series of the lowest monthly discharge was performed for the Baltic Sea drainage basin rivers as well. In the long–time period (1901–1990), the trend of the lowest monthly discharge (see Table 6) is positive in the Luleaelven. The regulation of this river runoff increased low flow gradually. There is no significant trend in the Nemunas low flow and significant negative trend in the Neva low discharges in the long–term period (1901–1990). The significant positive trends of the lowest monthly discharges were found in the Vistula and Oder in the long–term period. The changes of low flow could be influenced by the variability of precipitation associated with the climate change impact (Reihan et al. 2007).

The long–term anomalies of the lowest monthly discharge are less than the anomalies of the highest discharge. The variations of anomalies are from –20% to +20% in the Nemunas in the long–term period (Fig. 7a). Positive anomalies could reach 60% in the Neva River. Very high negative anomalies (to 80%) were found in the Luleaelven lowest monthly discharge in

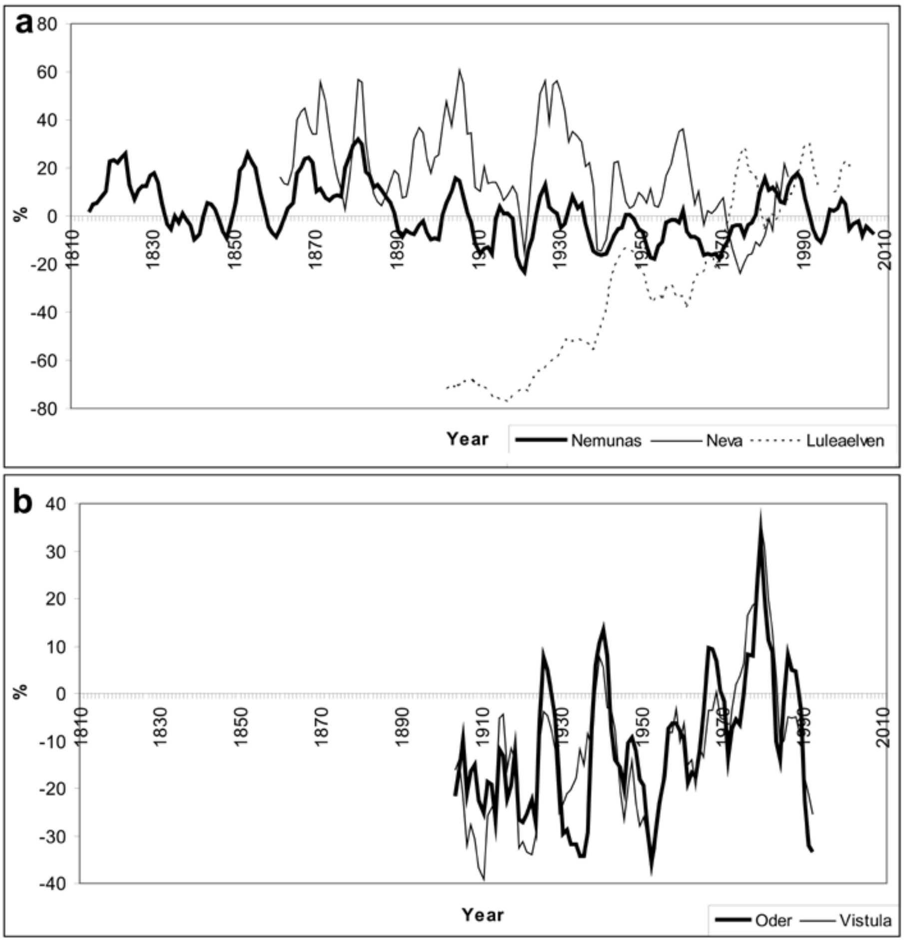

Fig. 7. Long–term anomalies (5-year moving average) of the lowest monthly discharge of the reference period of 1961–1990 (%): a) the Nemunas, Neva and Luleaelven rivers, b) the Oder and Vistula rivers. Compiled by D. Jakimavičius, D. Šarauskienė.

the beginning of the long–term period. The installation of dam cascades increased low discharge in the river (anomalies decreased as well). The Luleaelven was especially affected by high regulation after 1968; and anomalies of the lowest monthly discharge became positive from this year. The anomalies of the lowest discharge are almost synchronic in the Vistula and Oder (Fig. 7b).

During low water periods, the dates of the lowest monthly discharges in different rivers are different. In the Oder, Vistula and Nemunas, minimum discharges occur in August-September and in rare cases in January or February (Fig. 8), whereas in the Neva basin, the discharges reach their lowest limits solely in winter.

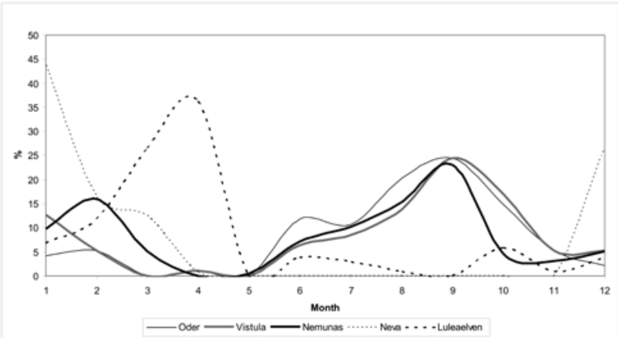

Fig. 8. Percentage distribution of the months when the lowest monthly discharges were detected in the rivers. Compiled by D. Jakimavičius, J. Kriaučiūnienė.

Here spring flood begins just after the ice melts, it lasts long, and the low water period begins later because the Neva River basin has a high amount of lakes. A similar runoff variation is observed in the Luleaelven basin, but because this basin is further north than the Neva basin, minimum discharges are recorded later, i.e. in March-April.

DISCUSSION

The trend analysis was performed for the evaluation of the tendencies of changes in the river discharges. There are no significant trends in long–term series (1901–1990) of annual discharge of the investigated rivers (Table 6). Similar tendencies of annual discharge changes during the long period were determined in the rivers of Sweden and the Baltic States (Lindström, Bergstrom 2004; Reihan *et al.* 2007). However, the tendency of the trend depends on the analyzed period (Reihan *et al.* 2007).

The cyclical variability of discharge was determined in the rivers of the Baltic Sea drainage basin. The wet and dry periods of one cycle continued about 13–13.5 years on the average. The durations of the wet and dry phases can differ in one–four years in the Nemunas and Neva and only in one–two years in the Oder and Vistula. The wettest phases of runoff of the Nemunas and Neva were in 1922–1936 and 1924–1936 respectively (deviations from the average are 14 and 12%). In the Oder and Vistula, the wettest phases were in 1965–1981 and 1965–1982 respectively (deviations are 15 and 19%). Approximately in the same period (1963–1977), the driest phase was in the Nemunas runoff with a deviation of 16%. It means that the dry phases have a time lag of about 12 years comparing the annual discharges of the Nemunas and Neva with the Oder and Vistula. Similar results were obtained from the analysis of long–term discharges series of 18 European rivers (Pekarova *et al.* 2006). The dry and wet phases in the rivers of West/Central Europe precede the peaks in North Europe by 12 years. The time lag increases with the distance between the basins.

The reason of this time lag could be various geographical and hydrometeorological factors influencing formation of river runoff. The runoff formation and distribution during a year is closely linked to air temperature and precipitation. The rivers of Central Europe, the Oder and Vistula, are in the zone of warmer climate than the rivers of Nord/East Europe, the Neva and Nemunas (the average temperature is about 8º and 6º respectively) (Zveryaev 2007). The average amount of precipitation also differs: from 700 mm in the Nemunas and Neva to 550–600 mm in the Oder and Vistula. The headwaters of the Oder and Vistula are in the mountains, while the Nemunas and Neva are the rivers flowing in the plains. The snowmelt spring floods dominate in the Nemunas and Neva river basins. Maximal spring floods affected by the combination of rainfall and snowmelt occur in the Vistula and Oder (Lajczak *et al.* 2006); in summer heavy rainfall may occasionally cause extreme stream–flow as well. Variability of the river runoff depends on the above described natural factors.

The changes of average annual discharge during the cycle periods (Table 4) are shown in Fig. 9. Tendencies of annual discharge decrease may be noticed in all investigated rivers. The average discharge of the Nemunas River was 535 m³/s in 1812–2009 and 480 m³/s in 1991–2009. The decrease of annual discharge by 10% was estimated. The similar tendency of decreasing discharges (12% and 9%) was determined in

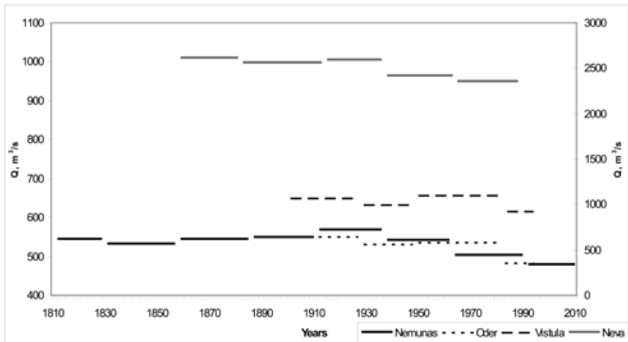

Fig. 9. The changes of average annual discharge during the cycle periods (Table 4) for the Nemunas and Oder (left axis of Y) and for the Vistula and Neva (right axis of Y). Compiled by B. Gailiušis.

the Vistula and Oder rivers comparing the average discharge of long–term series with the average discharges of the recent years.

The decrease of river runoff in the recent years is under the influence of the changes of temperature and precipitation. According to the **fourth assessment report** of the Intergovernmental Panel on Climate Change (**IPCC**), a significant climate change has already started (Solomon *et al.* 2007). The average temperature of winter and spring seasons increased at the mid-latitudes. Winters are getting warmer in the North of Europe (Lindström *et al.* 2006). The air temperature changes were identified in the Baltic countries as well (Reihan *et al.* 2007): winters became warmer and the contrast between the seasons decreased in the last decades of the 20th century. These are the reasons of the redistribution of runoff throughout a year (a strong increase of winter runoff and the tendency of decreasing spring floods) and the decrease of annual river discharge in the recent years.

CONCLUSIONS

The long–term variability in discharge time series of the selected rivers from the Baltic Sea drainage basin was identified. Cyclical variation of dry and wet phases in the annual discharge data series is characteristic in the Nemunas, Neva, Vistula and Oder. One dry or wet phase continues for about 13–13.5 years and the whole period of cycle is 26–27 years. Variability of river runoff depends on the natural factors, especially on the cyclic variation of precipitation. However, dry and wet phases in the different rivers do not occur at the same time. The dry phases have a time lag of about 12 years comparing the annual discharges of the Nemunas and Neva with the Oder and Vistula. The runoff of the Luleaelven is especially affected by high regulation. Therefore, variability in discharge of this river is contrary to the nature of the remaining investigated rivers. The floods decreased and the lowest flow increased due to the installation of dam cascades. Only the availability of long–term data series enables estimating the factors of both natural and anthropogenic origin that can influence river runoff variability.

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