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Spatial and temporal runoff oscillation analysis of the main rivers of the world during the 19th–20th centuries

Pavla Pekárová[a,*], Pavol Miklánek[b,1], Ján Pekár[c,2]

[a]Institute of Hydrology of Slovak Academy of Science, Racianska 75, 838 11 Bratislava, Slovakia
[b]Institute of Hydrology of Slovak Academy of Science, Racianska 75, 838 11 Bratislava, Slovakia
[c]Department of Economic and Financial Models, Comenius University, Mlynska dolina, 842 48 Bratislava, Slovakia

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Abstract

The annual discharge time series of selected large rivers in the world were tested for wet and dry periods. The 28–29-years cycle, as well as 20–22-years cycle of extremes occurrence were identified. From the trend analysis it follows that the hydrological characteristics of the rivers must be stated at least for one 28-year period. If we want to identify any trend uninfluenced by the 28-year periodicity of the discharge time series, we must determine the trend during a single or multiple curve cycle, starting and terminating by either minima (e.g. 1861–1946 in West/Central Europe) or maxima (e.g. 1847–1930 or 1931–1984 in West/Central Europe). Trends determined for other periods are influenced by the periodicity of the series and depend on the position of the starting point on the increasing or recession curve. Long-term trends during the period 1860–1990 have not been detected for the West/Central European runoff.

Further, the temporal shift in the discharge extremes occurrence (both, maxima and minima) was shown to depend on the longitude and latitude. The time shift between Neva and Amur discharge time series is about four years, between Amur and St Lawrence is about 16 years, and between St. Lawrence and Neva is about nine years. The time shift between Congo and Amazon is about seven years.

Keywords: Long-term runoff fluctuation; Discharge; Time series analysis; Spectral analysis; Temporal pattern; Teleconnection

1. Introduction

The development of mankind has depended on availability of water resources. Already the first agricultural civilisations noticed the temporal variability of water resources and oscillation of the dry and wet periods.

Statistical analysis of the runoff oscillations depends on availability of long time series of data. Systematic measurements of discharge in modern era started relatively late. The longest time series are available in Europe, but they do not exceed 200 years (Probst and Tardy, 1987). Such long series are exceptional and in most of the world only much shorted series exist.

* Corresponding author. Tel.: +421-2-44259311; fax: +421-2-44259311.
E-mail addresses: pekarova@uh.savba.sk (P. Pekárová), miklanek@uh.savba.sk (P. Miklánek), pekar@fmph.uniba.sk (J. Pekár).
[1] Tel/Fax: +4212-44259311.
[2] Tel.: +4212-60295713; fax: +4212-65412305.

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Forty years ago, Williams (1961) investigated the nature and causes of cyclical changes in hydrological data of the world. He attempted correlation between hydrologic data and sunspot with varying success. Brázdil and Tam (1990), Walanaus and Soja (1995), Sosedko (1997), Smith et al. (1997) and Lukjanetz and Sosedko (1998) found several different dry and moisture periods (2.6; 3.5; 5; 13.3-year) in the precipitation and discharge time series in Europe. Using an improved numerical procedure the variance contribution of both, the luni-solar 18.6-year and 10–11-year solar cycle signals to 3234 yearly sampled climate records were studied by Currie (1996) and Probst and Tardy (1987) studied mean annual discharge fluctuations of fifty major rivers distributed around the world by filtering methods. They showed, that North American and European runoffs fluctuate in opposition while South American and African runoffs present synchronous fluctuations.

The changes of runoff in last decades may by related to climate change, but there exist also other natural factors that influence the runoff variability and may reinforce the runoff changes. The hydrologists and climatologists concentrate on the relationship between both, precipitation and runoff variability and large air pressure oscillations over the oceans during the last 15 years. A typical example is the SO (Southern Oscillation) over the Pacific (Rodriguez-Puebla et al., 1998) and NAO (North Atlantic Oscillation) over the Atlantic Ocean (Hurrell, 1995; Stephenson, 1999; Stephenson et al., 2000). The change of air pressure fields over large areas influences the transport of amount of precipitation over neighbouring continents.

For example Shorthouse and Arnell (1997) analysed relationships between inter-annual climatic variability—as measured by the NAOI—and spatial patterns of anomalous hydrological behaviour across Europe. The analysis was based on regional average monthly discharge series, derived from 477 drainage basins on the FRIEND European Water Archive between 1961 and 1990. It was shown that European river flows are strongly correlated, most particularly in winter, with the NAO and that this relationship exhibits a strong spatial pattern. Northern European river flows, particularly in the Scandinavian region, tend to be positively correlated with the NAOI, and rivers in southern Europe reveal negative correlation with the index. This result is consistent with the previously explored correlation between the NAO and precipitation.

Cluis (1998) shows that in most areas of the Asia-Pacific region, a strong El Niño related signal can be found in the historical river series stored at the Global Runoff Data Center (GRDC). This signal is particularly strong in the Australian rivers whose regimes are known to be highly contrasted. Cluis showed that during El Niño the runoff is lower in these areas, while during La Niña it is higher than the mean runoff (despite the fact that for some of the New Zealand rivers the results were contrary).

Yang et al. (2000) investigated the ENSO teleconnection with annual precipitation series (Tiberian Plateau, China) from 1690 to 1987 (nearly 300 years). The results showed that negative precipitation anomalies are significantly associated with El Niño years.

On the other hand Kane (1997) investigated, that the relationship between El Niño and droughts in north–east Brazil is poor. Thus, forecasts of droughts based on the appearance of El Niño alone would be wrong half the time. Instead, predictions based on significant periodicities (ca 13 and ca 26 years) give reasonably good results.

Our previous analysis of the long-term runoff oscillation shows the regular dry and wet periods occurrence in central Europe (Pekárová, 2002; Pekárová and Pekár, 2002; Svoboda et al., 2000). The scope of the study is:

(i) To demonstrate the existence of the long-term discharge fluctuations (20–30 years) in rivers of all continents;
(ii) To pronounce the hypothesis of the shift in long-term runoff extremes occurrence over the earth.

2. Temporal and spatial discharge analysis of main world rivers

2.1. Material

The longest available time series of mean annual discharge of the selected world largest rivers were used to analyse the long-term runoff oscillation.

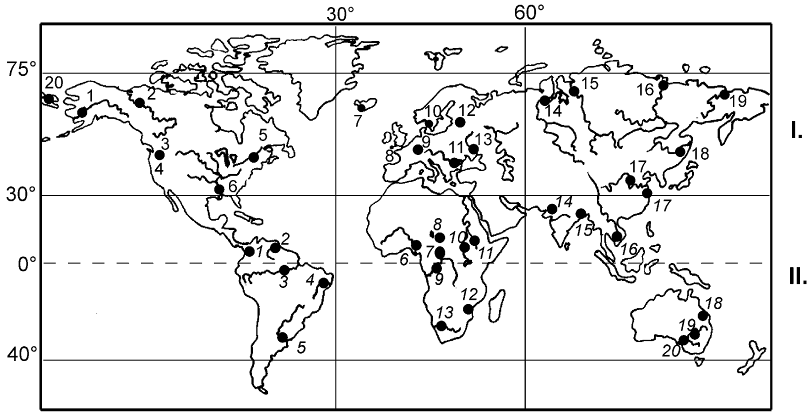

Fig. 1. Gauging stations localisation on selected rivers (legend in Table 1).

The annual precipitation time series are usually the basis for study of the long-term oscillation of dry and wet periods in the basin. We will analyse the annual discharge time series due to following reasons:

- The increase of precipitation by one third may increase the runoff by one half. Therefore changes in precipitation series are even more evident in discharge series.
- The water balance of the basin depends not only on precipitation, but on temperature as well (evapotranspiration). The discharge series combine both these influences.
- The problems of precipitation measurements and evaluation of the areal precipitation in mountain basins are well known. Discharge measurement in the outlet profile of the basin is simpler and more accurate in comparison to areal precipitation.
- The analyses of the long-term runoff oscillations of the large rivers eliminates the local disturbances in precipitation and temperature series due to local orographic peculiarities.

The long annual discharge data series of all the continents were obtained from following data sources:

(i) Global Runoff Data Center in Koblenz, Germany;
(ii) CD ROM of the Hydro-Climatic Data Network (HCDN), US Geological Survey Streamflow Data Set for the United States;
(iii) CD-ROM World Freshwater Resources prepared by Shiklomanov in the framework of the International Hydrological Programme (IHP) of UNESCO;
(iv) URL http://waterdata.usgs.gov.

A set of more than a hundred of annual discharge time series with long periods of observation in all continents were analysed in the study. The river basins were grouped into two regions:

I. Extra tropics zone of the Northern Hemisphere (between 30 –75 °N);
II. Equatorial zone and mild zone of the Southern Hemisphere (30 °N–40°S).

For the final analysis twenty river basins were selected in each region. The selected rivers and stations are in Fig. 1. In Table 1 there are basic hydrologic characteristics of the series and basins.

In Fig. 2 there are shown the smoothed yearly discharge of selected rivers of all the continents by resistant non-linear smoothing technique. The raw data were filtered by two filters in order to attenuate the short-range fluctuations and to extract the long-range climatic variations. In the first step, the 5-years moving medians were computed from the original data. (Medians are not as sensitive on isolated extreme values as the averages are). In the second step, the 5-years weighted moving averages were computed from the medians according to

Table 1
Gauging stations localisation and basic hydrologic characteristics: C—country of the station, A—area [10^3 km^2], period of observation (since—to), Qa—mean annual discharge [m^3s^{-1}], qa—mean annual yield [$l.s^{-1}km^2$], cs—coefficient of asymmetry, cv—coefficient of variation, min/max–minimal/maximal mean annual discharge [m^3s^{-1}]

	River	Station	C[a]	A	Since	To	Qa	qa	cs	cv	min	max
1	Yukon River	Mouth[b]	US	850	1945	1988	6189	7.2	0.46	0.25	2617	10249
2	Mackenzie River	Mouth	CN	1790	1948	1988	10338	5.8	0.75	0.09	8799	13245
3	Fraser River	Hope	CN	217	1912	1984	2722	12.5	0.29	0.13	1939	3673
4	Columbia	Mouth	US	668	1878	1989	7454	11.2	−0.23	0.18	4510	10375
5	St.Lawrence	Ogdensburg, N.Y.	US	765	1860	1998	6986	9.1	0.04	0.10	5219	8946
6	Mississippi	Mouth	US	2980	1914	1988	16069	5.4	0.48	0.23	8830	27657
7	Thjorsa	Urridafoss	IC	7	1947	1993	364	50.6	0.55	0.12	289	477
8	Loire	Mouth	FR	120	1921	1986	838	7.0	0.72	0.33	282	1967
9	Rhine	Koeln	DE	144	1816	1997	2089	14.5	−0.03	0.19	920	3227
10	Vaenern–Goeta	Vaenersborg	SE	47	1807	1992	535	11.4	−0.10	0.19	225	768
11	Danube	Orsova (1971:Turnu Severin)	RO	576	1840	1988	5438	9.4	0.48	0.17	3339	8053
12	Neva	Novosaratovka	RS	281	1859	1984	2503	8.9	0.18	0.17	1341	3674
13	Dniepr	Locmanskaja Kamjanka	UA	495	1818	1984	1627	3.3	0.77	0.33	673	3375
14	Ob	Salekhard	RS	2950	1930	1994	12532	4.2	0.39	0.15	8791	17812
15	Yenisei	Igarka	RS	2440	1936	1995	18050	7.4	0.20	0.08	15543	20966
16	Lena	Kusur	RS	2430	1935	1994	16619	6.8	0.48	0.12	12478	22626
17	Songhua	Harbin	CH	391	1898	1987	1202	3.1	0.53	0.40	386	2671
18	Amur	Khabarovsk	RS	1630	1896	1985	8569	5.3	1.15	0.25	4281	18593
19	Kolyma	Sredne–Kolymsk	RS	361	1927	1988	2199	6.1	0.36	0.22	1337	3481
20	Amguema	Mouth of South Brook	RS	27	1944	1984	338	12.7	0.79	0.32	168	637
1	Magdelena	Mouth	CO	260	1904	1990	7139	27.5	0.26	0.08	5361	9587
2	Sao Francisco	Juazeiro	BZ	511	1929	1994	2692	5.3	1.03	0.30	1603	4798
3	Amazon	Obidos	BZ	4640	1928	1996	174069	37.5	−0.24	0.10	138555	206941
4	Orinoco	Puente Angostura	VN	836	1923	1989	30932	37	0.42	0.10	21245	44702
5	La Plata	Mouth	AR	3100	1904	1985	25583	8.3	1.71	0.26	14191	58657
6	Oubangui	Bangui	CA	500	1911	1994	4116	8.2	−0.03	0.28	782	7360
7	Chari	Ndjamena(Fort Lamy)	CD	600	1933	1991	1119	2	1.63	0.48	236	3344
8	Niger	Mouth	NG	2090	1920	1985	9275	4	0.44	0.27	3931	15200
9	Congo	Kinshasa	CG	3475	1903	1983	39536	11.4	0.89	0.10	32253	53908
10	Blue Nile	Roseires Dam	SU	210	1912	1982	1548	7.4	−0.06	0.18	652	2199
11	White Nile	Malakal	SU	1080	1912	1982	939	0.9	1.53	0.19	714	1537
12	Zambezi	Mouth	MO	1330	1921	1985	4852	3.6	0.45	0.19	2551	8105
13	Oranje	Vioolsdrif	SA	851	1964	1986	150	0.2	1.08	0.80	30	449
14	Indus	Mouth	IN	960	1921	1985	7127	7.4	0.42	0.20	3974	11321
15	Ganges[c]	Mouth	BA	1730	1921	1985	43704	25.3	3.15	0.03	38222	53170
16	Mekong	Mouth	VI	810	1921	1985	15924	19.7	0.01	0.12	11794	19237
17	Yang–tze	Hankou	CH	1488	1865	1986	23266	15.6	0.12	0.10	14313	31983
18	Mary River	Miva	AU	5	1910	1995	38	7.9	1.28	0.90	4	147
19	Darling River	Bourke Town	AU	386	1943	1994	126	0.3	2.84	1.40	5	856
20	Murray	Mouth	AU	3520	1877	1988	760	0.2	2.59	0.75	38	4091

[a] AR—Argentina, AU—Australia, BA—Bangladesh, BZ—Brasilia, CA—Central Africa, CD—Chad, CG—Congo (Democratic Republic of), CN—Canada, CO—Colombia, DE—Germany, FR—France, CH—China, IN—India, IC—Iceland, MO—Mozambique, NG—Nigeria, RO—Romania, RS—Russia, SA—South Africa, SE—Sweden, SU—Sudan, UA—Ukraine, US—United States of America, VI—Vietnam, VN—Venezuela.
[b] Mouth specifies the data from Shiklomanov CD World Freshwater Resources, other data were provided by GRDC Koblenz.
[c] Ganges: delta of Ganges—Brahmaputra—Meghna.

formulae:

$$y_i = 1/16(x_{i-2} + 4{\cdot}x_{i-1} + 6{\cdot}x_i + 4{\cdot}x_{i+1} + x_{i+2}) \qquad (1)$$

The influence of different methods on data filtration was studied by Currie (1996) and Probst and Tardy (1987). Probst and Tardy (1987) compared three complementary filtering methods. They found a difference of one or two years for the localisation of maxima and minima discharges in filtered time series.

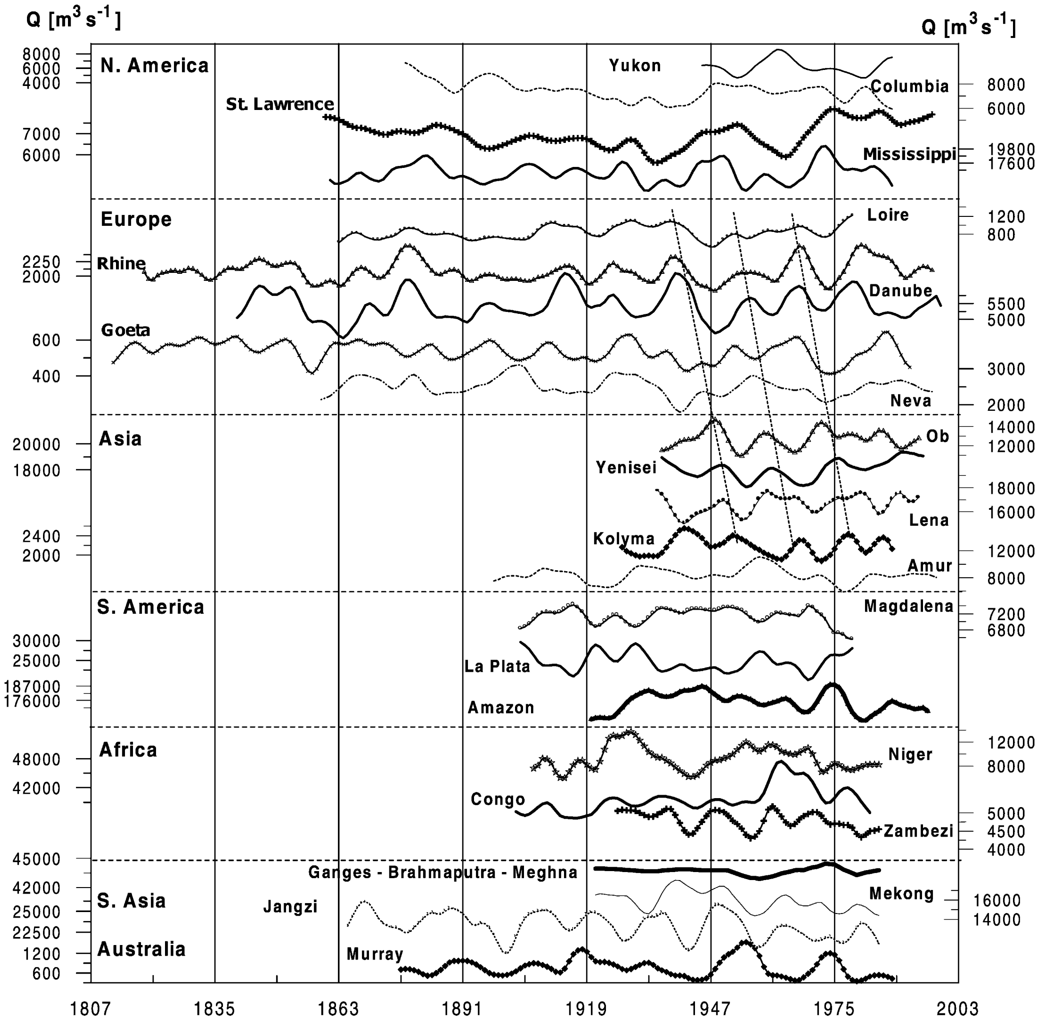

Fig. 2. Smoothed yearly discharge of selected rivers over the continents using two resistant non-linear smoothing techniques (the 5-years moving medians and the 5-years weighted moving averages).

2.2. Identification of the long-term runoff trend

2.2.1. Europe

In Europe, the longest discharge data series have been available since beginning of the 19th century. Therefore these series are particularly suitable to study the long-term runoff oscillations and trends.

In order to identify trends for some European rivers, discharge time series of eleven rivers for West/Central Europe were used (Goeta: Vaenersborg, SE (1807–1992), Rhine: Koeln, DE (1816–1997), Neman: Smalininkai, LT (1912–1993), Loire: Montjean, FR (1863–1986) Weser: Hann–Muenden, DE (1831–1994), Danube, RO (1840–1988), Elbe: Decin, CZ (1851–1998), Oder: Gozdowice, PL (1900–1993), Vistule: Tczew, PL (1900–1994), Rhone: mouth, FR (1921–1986), and Po: Pontelagoscuro, IT (1918–1979)) and six time series for East Europe (Dniepr: Locmanskaja Kamjanka (1818–1984), Neva: Novosaratovka (1859–1984), N. Dvina: Ust-Pinega (1881–1990), Don: Razdorskaya (1891–1984), Pechora: mouth (1921–1987), and Volga: mouth (1882–1998)).

These data series were completed by the multiple regression methods and the standardised average discharge time series was computed. Comparisons of the following pairs of four standardised discharge data filtration methods were made:

1. *3-9-MA*—3-years Moving Average (MA) and 9-years MA.
2. *e3s21*—Exponentially Weighted Moving Average (EWMA)-smoothing constant 0.3 and Spencer's 21 MA.
3. *r5h11*—5RSSH filter (a non-linear smoothing technique that includes a median for a value and five points around that value, Resmoothing (R), two Splitting operations to eliminate flat segments in the data (SS), and a Hanning weighted average with weights 0.25, 0.5, and 0.25 (H)), and Henderson's 11-years MA.
4. *h5sp21*—Henderson's 5-years moving average and Spencer's 21 MA.

The course of the filtered standardised discharge data of the West European time series are given in Fig. 3a, of East Europe in Fig. 3b, and of Europe in Fig. 3c.

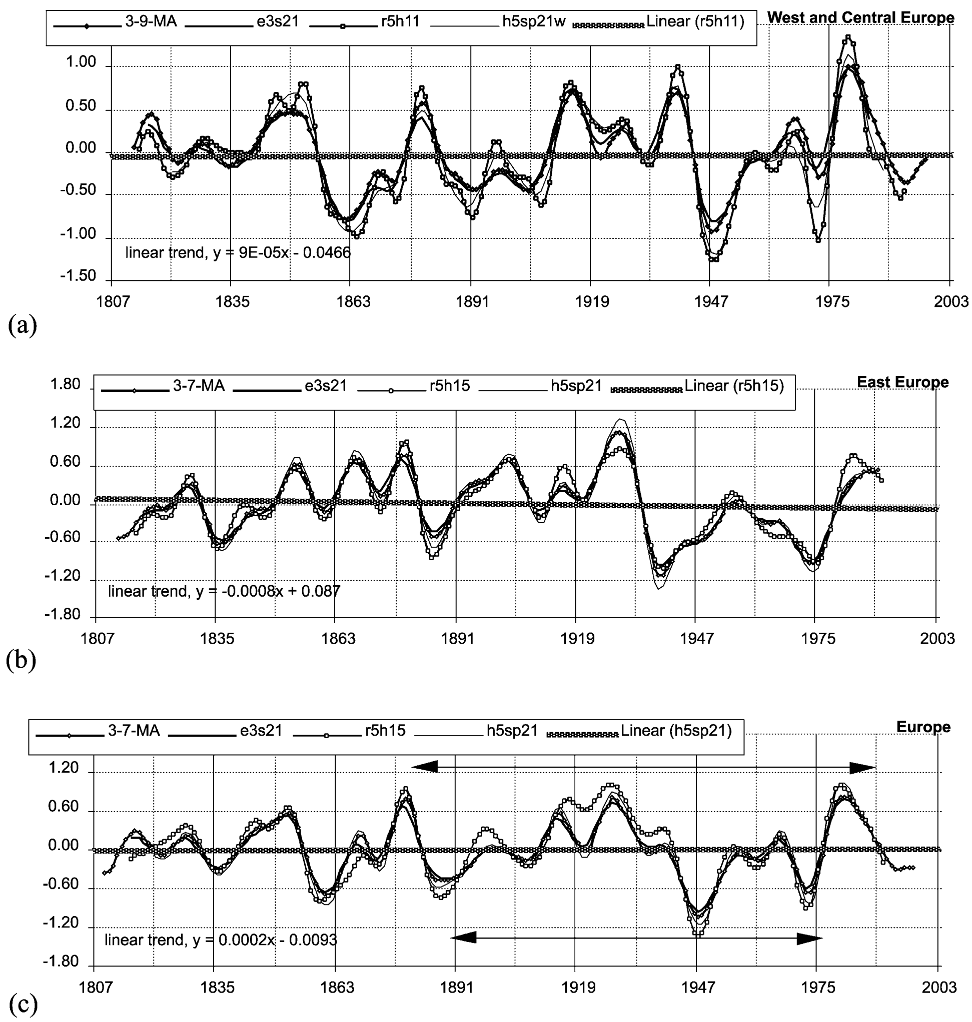

Fig. 3. The course of runoff fluctuation and trends in Europe during 1810–1990. (Smoothed standardised discharge data. (a) West/Central Europe, (b) East Europe (excluding Volga), (c) Europe (excluding Volga).

If we want to identify any trend uninfluenced by the 28-year periodicity (this periodicity will be shown later in the paper) of the discharge time series, we must determine the trend during a closed multiple loop, starting and terminating by either minima (e.g. 1861–1946 in Central Europe) or maxima (e.g. 1847–1930 or 1931–1984 in Central Europe). Trends determined for other periods are influenced by the periodicity of the series and depend on the position of the starting point on the increasing or recession curve.

The trend analysis does not show any significant trend change in long-term discharge series (1810–1990) in representative European rivers (Fig. 3a). Nevertheless, it is possible to identify multiannual cycles of wet and dry periods. The dry period occurred in Europe around 1835 and the years 1857–1862 were very dry. In the 20th century the period 1946–1948 was very dry. Another dry period occurred in 1975. If we consider the 28-year cycle, described in next sections, we can expect the next dry period in Central Europe to occur in next years (around 2003).

The largest rivers in the Central Europe are Rhine and Danube. Both rivers are highly influenced by the Alps and their long-term variability of runoff is very similar (Fig. 2). The north–eastern European rivers, e.g. Neman, Neva, Pechora, Northern Dvina, as well as south–eastern European rivers Dnieper, Don, Ural and Volga show very similar occurrence of the dry periods. The Neva river drains the large Finnish and Russian lake basins (Arpe et al., 2000). The big lake rivers are very suitable for the identification of the long-term-multiannual cycles, as the lakes eliminate and smooth the annual variability of the dry and wet years.

2.2.2. Northern Asia

The regular decrease and increase of discharge is observed in the large rivers of Russia–Siberia (Ob, Yenisei, Lena, Kolyma). Systematic observation of discharge of these rivers started only after 1930. The length of these series is sufficient for identification of the 14-year cycle (Lukjanetz and Sossedko, 1998), only. However, the 28-year cycle can be found in the Amur river.

In these rivers the maximum and minimum values do not occur in the same years (see Fig. 2), e.g. a local maximum occurred in 1972 on Ob, in 1975 on Yenisei, and in 1980 on Kolyma. The time shift (delay) of the extremes in eastward direction will be analysed by cross-correlation in the next paragraph.

2.2.3. North America

The annual discharge data series of the largest rivers were used for the identification of the cycles (Mississippi, St Lawrence, Mackenzie, Yukon, and Columbia, see Fig. 2). The St Lawrence River, similar to Neva in Russia, drains a large lake district.

Unlike Europe, where it was very dry, the years 1945–1949 were wet in North America. The runoff extremes in Europe and in the North America do not occur in the same years. A prevailing wet period in Europe corresponds to a dry period in the North America. This hypothesis will be analysed by cross-correlation in next sections.

2.2.4. South America

Discharge series of three large rivers of the South America are in Fig. 2 (Amazon, Magdalena, La Plata). It is interesting that the series of Magdalena (Northern Hemisphere) create a mirror image of the La Plata series (Southern Hemisphere).

The discharge measurements of the world's largest river Amazon were unsound in the past. The available data series are ambiguous before 1950 and different values are published in different databases (e.g. GRDC or Shiklomanov 2000). If we compare Amazon's data to those of another large Equatorial river, Congo in Africa, we can observe a shift of several years in the extremes occurrence.

2.2.5. Africa

The alternating of the dry and wet periods is much stronger in African rivers compared to European ones. Whereas the time series of rivers in the Northern Hemisphere require smoothing by moving averages in order to identify the long-term discharge oscillations, the African rivers show the oscillations without smoothing.

The African rivers with relatively long discharge series are Niger, Congo (Fig. 2), White and Blue Nile (about 90 years). The length of the series is sufficient to prove the 14-years cycles only, but not longer ones. Unfortunately, no long discharge series are available in the South Africa.

The African rivers north of the Equator (Niger, Chari, Ubangi) have dry periods in the same years as the central European rivers, while the rivers southern of the Equator (Zambezi, Shire) have a reverse occurrence of the extremes. The Congo River is influenced by its tributaries from the Northern Hemisphere (Ubangi) as well as from the Southern Hemisphere (Kasai, Lualaba). From the long-term point of view the runoff of Congo is similar to the runoff of the White Nile, which drains the Victoria Lake situated exactly on the Equator.

2.2.6. South–eastern Asia and Australia

Cluis (1998) analysed trends of the Pacific and Asia rivers. According to his analysis the runoff decreased or remained stable between the Equator and 40°N at the end of the last century. In Australia the runoff did not change after elimination of the cyclic component.

The longest discharge data series in south–eastern Asia are those of Yangzi. The data show a regular 14-year cycle.

The Ganges (Ganges–Brahmaputra–Meghna) river is characterised by the steadiest runoff, and the coefficient of variation of the annual discharge is only 0.03. The mean annual discharge varies between 41 000 and 45 000 $m^3 s^{-1}$ except 1957 (38 221 $m^3 s^{-1}$) and 1974 (51 169 $m^3 s^{-1}$). The long-term runoff is relatively constant.

Unlike Ganges the Australian rivers exhibit a clear periodicity and variability. The coefficient of variability of Darling discharge series is up to 1.36 (the minimum and maximum annual discharge was 5 and 856 $m^3 s^{-1}$, respectively). Cluis (1998) related the variability of runoff to El Niño and La Niña episodes.

Similar to South America and Africa, the occurrence of wet periods northern of the Equator in south–eastern Asia and Australia seems to go along with dry periods southern of the Equator (see Murray and Yangzi in Fig. 2).

2.3. Identification of the long-term periodicity

It is possible to identify the cyclicity or randomness in the time series by auto-correlation and periodogram. Both methods were used to look for the long-term cycles of runoff decrease and increase in the analysed runoff time series.

2.3.1. Brief overview of the spectral analysis of random processes

The spectral analysis is used to examine the periodical properties of random processes $\{x_i\}_{i=1}^{n}$. The spectral analysis generalises a classical harmonic analysis by introducing the mean value in time, of the periodogram obtained from the individual realisations (Nacházel 1978). The fundamental statistical characteristic of a spectral analysis is its *spectral density*.

The basic tool in estimating the spectral density is the *periodogram* (Venables and Ripley, 1999; Štulajter, 2001). A periodogram (a line spectrum) is a plot of frequency and ordinate pairs for a specific time period. This graph breaks a time series into a set of sine waves of various frequencies. It is used to construct a frequency spectrum. If the periodogram contains one spike, the data may not be random. The spectral density is defined as a mean value of the set of periodogram for $n \rightarrow \infty$.

The periodogram is calculated according to:

$$I(\lambda_i)=\frac{1}{2\pi n}\left|\sum_{\tau=1}^{n} x_\tau e^{-i\tau\lambda_j}\right|^2 =\frac{1}{2\pi n}\left\{\left(\sum_{\tau=1}^{n} x_\tau \cdot \sin(\tau\cdot\lambda_j)\right)^2+\left(\sum_{\tau=1}^{n} x_\tau \cdot \cos(\tau\cdot\lambda_j)\right)^2\right\}. \tag{2}$$

We compute the squared correlation between the series and the sine/cosine waves of frequency λ_j. By the symmetry $I(\lambda_j)=I(-\lambda_j)$ we need only to consider $I(\lambda_j)$ on $0 \le \lambda_j \le (\pi$.

For real centred series the periodogram $I(\lambda_j)$ can be estimated by auto-covariance function as

$$I(\lambda_j) = \frac{1}{2\pi}\cdot\left(R_0 + 2\sum_{\tau=1}^{n-1} R_\tau \cdot \cos(\tau\cdot\lambda_j)\right), \tag{3}$$

for Fourier frequencies:

$$\lambda_{j'} = \frac{2\pi \cdot j}{n}, \quad \text{where } j = \left\langle 1, \frac{n}{2} \right\rangle \tag{4}$$

2.3.2. Combined periodogram method

It is clear that from the relationship Eq. (4) it follows that for low frequencies, i.e. for long periods, we compute the periodogram with a sparse step. For example, if a time series is 100 years long, the periodogram is only computed for periods of $100/2 = 50$ years, $100/3 = 33.3$ years, $100/4 = 25$ years, etc. If the real period is of 29 years, then we do not get the correct period. This is why it is necessary to pay the maximum attention to the analysis and not to rely only on results provided by mathematical tests without the appropriate analysis.

One way how to reveal the real period is decreasing the length of the measured series, i.e. computing the periodogram for different 'random' selections of the series followed by computing the average value of the periodogram. The result of this process we will name as *combined periodogram*. In order to obtain such a combined periodogram a code PERIOD was written. This program computes periodogram for series successively shortened by two years (Pekárová, 2002).

2.3.3. Results

Neva and St. Lawrence rivers are very suitable for study of the long-term runoff oscillations, because the variability is smoothed by the great water accumulation in the lakes they drain.

As an example, there are the auto-correlations and periodograms of St. Lawrence (North America), Neva (Europe), Amur, Yangzi (both Asia), and Congo (Africa) in Fig. 4. There were used raw data.

The auto-correlation and periodogram of St Lawrence River show very marked 30-year periodicity of runoff increase and decrease. In Amur time series there is the 28-year period combined with the 14-year period. In Rhine, Yenisei, Lena, Yangzi, Congo, and Amazon time series the 14- and 7-years periods are more evident. We must realise that the 28-year period could not be identified due to short time series.

Hydrological time series are of maximum length of 200 years. Using periodograms in order to identify the significant periods can lead to important errors. This is why a new, above described, method of combined periodogram was used.

To illustrate the proposed method we analysed an artificial series of the length of 1999 members (years) that was created as a cosine combination of three periods 29, 11, and 6.4 years. If we analyse this series in the ordinary way (1999 members), we get a periodogram as it is shown in Fig. 5a Here, all three periods are clearly identified. The length of the series of 1999 members is sufficient for exact identification of long-term 30–50 years periods.

If we draw a periodogram on the basis of a 79 year time series (in the case we have only a 79 year series of observations), among the long periods we get a significant period of 26.3-year (see Fig. 5b). On the other hand, if we draw a periodogram on the basis of a 99 year time series (in the case we have a 99 year series of observations), among the long periods we get a significant period of 33 years (see Fig. 5c). Hence, the difference in the long period identification is significant.

The combined periodogram method sufficiently thickens the spectrum. In the spectrum a 28–30 years spike, which at best corresponds to the reality, gets distinct (Fig. 5d).

In Fig. 6 you can see combined periodograms of such sixteen rivers from different continents that have the longest discharge time series. For these rivers the cycles of about 3.6–4; 6–7; 11; 14; 20–22; and 26–30 years were identified. The longest cycle of about 26–30 years was found for Neva, Goeta, Danube, Amur, La Plata rivers. In the data of Yangzi, Rhine, Vltava, Ural, Mississippi, Congo, and Amazon an about 14 years cycle dominates. For these river another 7 years cycle can be identified. Another significant cycle of 20–22-years can be found for Murray, Zambezi, Vltava (CZ), Danube, Dniepr, and St Lawrence.

The auto-correlation analysis leads to similar results; see the auto-correlation of Rhine River raw discharge series in Fig. 7a. Here, it is difficult to identify the 14-years period. But if we plot the 3-years moving averages of the auto-correlation coefficients (Fig. 7b), the 14-years period becomes

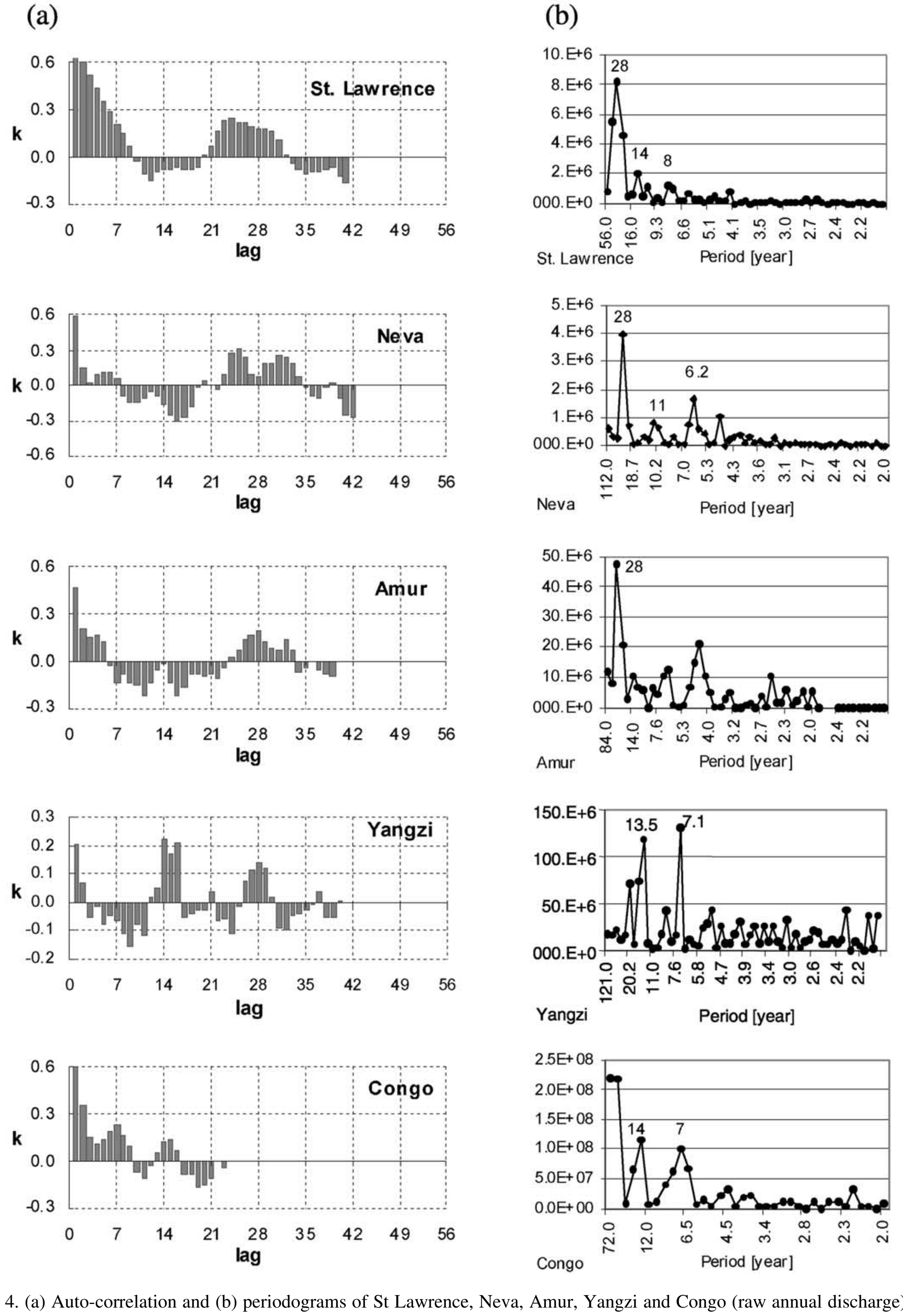

Fig. 4. (a) Auto-correlation and (b) periodograms of St Lawrence, Neva, Amur, Yangzi and Congo (raw annual discharge).

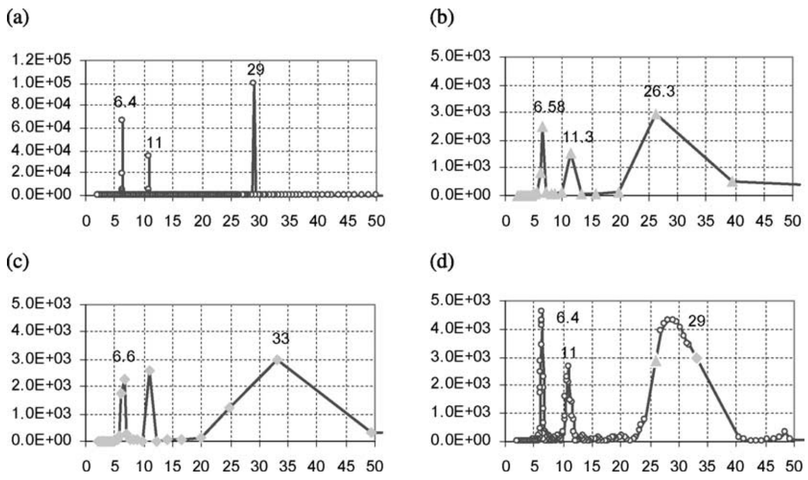

Fig. 5. (a) Periodogram on the basis of a 1999 year time series; (b) Periodogram on the basis of a 79 year time series; (c) Periodogram on the basis of a 99 year time series; (d) Combined periodogram on the basis of a 99 year time series.

visible. Seven wet years alternate seven dry years. Due to sufficient length of the Rhine time series (181 years), the length of the cycles is faithful.

2.3.4. Fisher–Whittle test

The significance of the appropriate periods was tested by Fisher–Whittle test. The test is based on the assumption that the periodical part of the time series x_t is overlapped by a sequence of random numbers y_t so we can write

$$x_t = \bar{x} + \sum_{j=1}^{m} (A_j \cos(\lambda_j t) + B_j \sin(\lambda_j t)) + y_t$$

$$t = 1, \ldots, n \tag{5}$$

where the sum represents the deterministic part of the model while y_t represents the sequence of random numbers. This means that x_t is not stationary. In the test, the null-hypothesis that the sequence $x_1, \ldots, x_n$ is a sequence of independent and identically distributed random variables with distribution $N(0, \sigma^2)$ is stated against the alternative hypothesis that Eq. (5) is true.

The test runs as follows: The tested values I_j are reordered in a non-increasing sequence—$I_1, \ldots, I_m$ and the test statistics W_1 of the form

$$W_1 = \frac{I_1}{I_1 + I_2 + \cdots + I_m} \tag{6}$$

is calculated and compared to the critical value of the Fisher distribution. For given significance level α the critical value $W_{k,\alpha}$ can be estimated according to the formula

$$W_k = 1 - \left(\frac{\alpha}{m}\right)^{\frac{1}{m-1}} \tag{7}$$

Since we are interested in the case when the null-hypothesis is rejected, a comparison of the test statistic W_1 to the critical values $W_{k,\alpha}$ for such values of α when $W_1 > W_{k,\alpha}$ gives us the significance of W_1. The critical value of α's (such α for which $W_1 = W_{k,\alpha}$, i.e. test breaks from acceptance to rejecting the null-hypothesis) can be approximated by the formula

$$p_0 = (1 - W_1)^{m-1} \tag{8}$$

In the case of significance of W_1 Whittle suggests the following modification of the Fisher test: after excluding the highest value V_1 from the sequence we repeat the test for the shortened sequence $(I_2, I_3, \ldots I_m)$, using the test statistic

$$W_2 = \frac{I_2}{I_2 + I_3 + \cdots + I_m} \tag{9}$$

If test provides the significance of the value I_2, we continue the test for the rest of values or until an insignificant value is found.

Data resulting from Fisher–Whittle test for Neva (141, 131, and 121 year time series), Danube (161, 151, and 141 year time series), and Goeta (181, 171, and 161 year time series), are presented in Table 2.

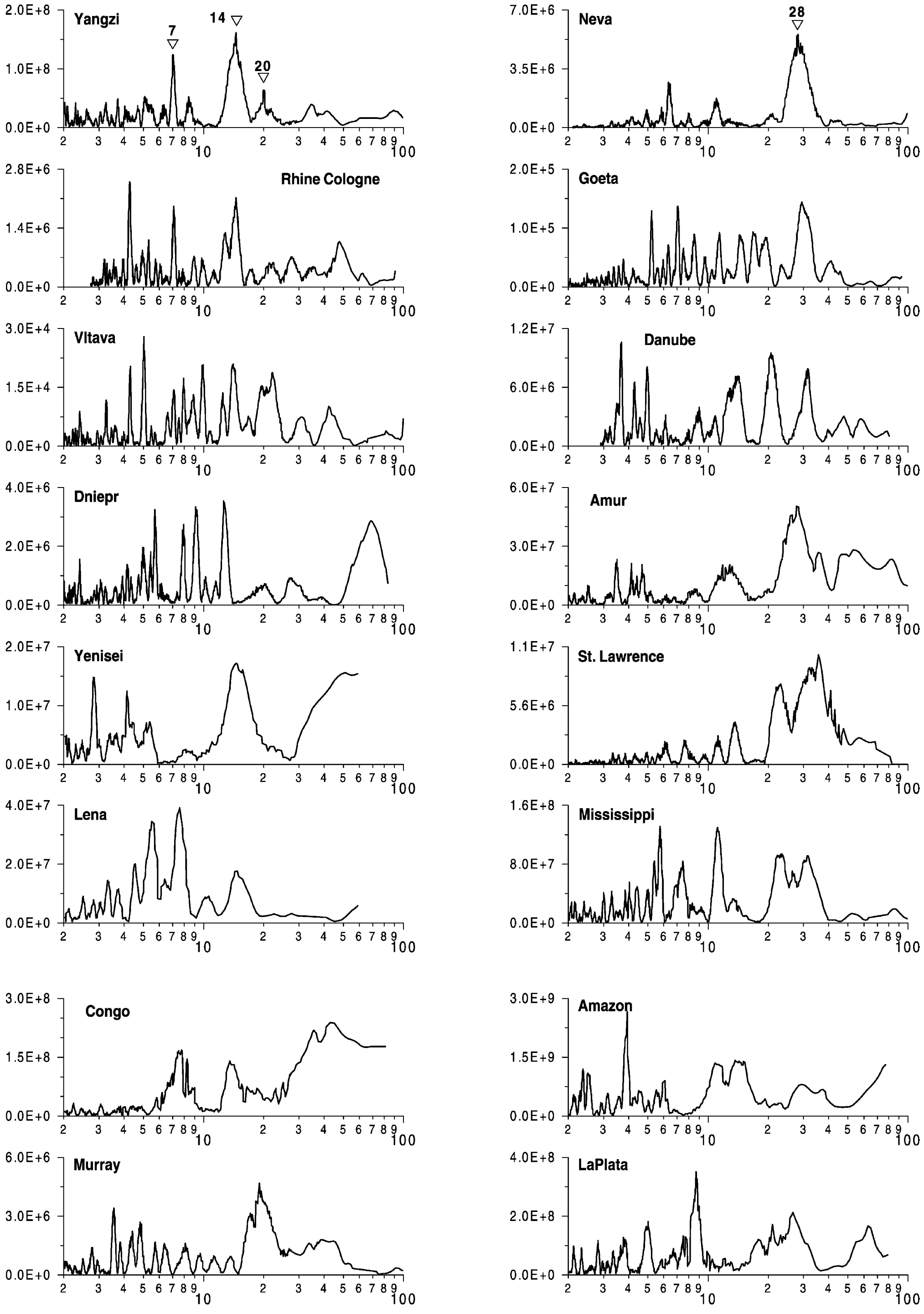

Fig. 6. Combined periodograms of sixteen rivers.

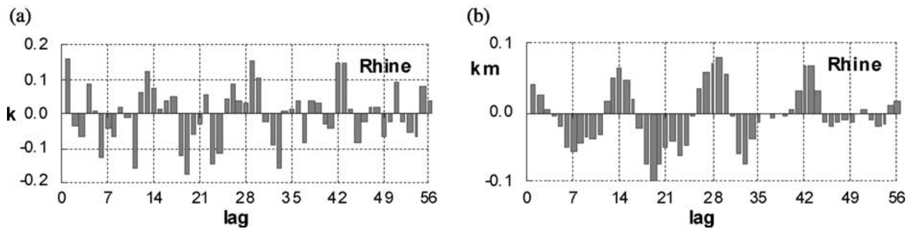

Fig. 7. (a) Auto-correlation coefficients and (b) 3-years moving averages of the auto-correlation coefficients of the Rhine river.

The null hypothesis that the time series for the Neva River is random can be rejected for the 28.2-year period almost with certainty. In the case of the Danube river (151 years' data), periods of 3.68, 20.14 and 30.2 years are significant, while in Goeta river 7, 14.64, and 30.17 years significant cycles were found. From the algorithm of periodogram calculations it follows that if the real length of period is P years, then the Fisher–Whittle test gives best results when the length of the time series, n, is a multiple of P.

3. Identification of the shift of extremes

Cross-correlation analysis was used to find the discharge relation between two rivers. The correlation coefficients, r, between two discharge series were repeatedly computed for time shifts of 0, 1, 2, 3,··· years. The cross-correlation coefficients between Danube and Rhine discharge series are plotted in Fig. 8a. The Figure shows an existence of a direct relation (without time shift) between raw annual discharge series of Danube and Rhine. The coefficient of correlation for the zero shift is equal to 0.617.

A similarly evident relation is between Goeta and Neva raw discharge series (Fig. 8b). In the plot of cross-correlation coefficients we can also see the 28-year cycle of wet and dry periods. In case of these lake rivers we can also observe the dependence of runoff on previous years.

The cross-correlation analysis of rivers in different longitudinal zones indicates the shift in extremes occurrence. It can be demonstrated by comparison of large European and Asian rivers in Russia (Fig. 9). The same results were obtained by Probst and Tardy (1987).

The shift of the discharge extremes between Neva and Ob is about 3 years, between Ob and Lena 3 years, and between Lena and Kolyma 7 years. The total shift between Neva and Kolyma is about 13 years.

The cross-correlation analysis of St. Lawrence and Neva raw discharge series (Fig. 10) shows the shift in extremes occurrence as well. The regular cyclicity of the correlogram follows from the 28-year periodicity of Neva and St. Lawrence discharge series.

Keeping the eastward orientation of the shift demonstrated at the Siberian rivers, we will allege Neva—St Lawrence shift of about 18 years.

Cross-correlation between Thjorsa (Iceland) and Goeta (Sweden) is in Fig. 11a . The coefficient of correlation between two series is $r = -0.55$. The relatively high negative correlation means, that during dry period in Scandinavia there is a wet period in Iceland. The shift of extremes occurrence is about seven years.

Cross-correlation of Congo and Amazon, two of the world largest rivers, gives also interesting results. The wet and dry periods do not occur in the same years.

4. Conclusion

The aim of the study was to look for the cycles of the alternating dry and wet periods in the available discharge time series of the selected large rivers of the world. We identified the 14-year cycle (about seven dry years alternated by seven wet years), amplified by the 28-year cycle, and 20–22- years cycle in some regions. Of course, the cycles are not regular, but in the long-term mean (about 180 years) they are near the mentioned values.

The statistical analysis of the available long discharge series of the selected large rivers of the world shows the main 3.6-, 7-, 13–14-, 20–22-, and 28–32-years cycles of extreme river discharge.

Table 2
Results of Fisher–Whittle test for Neva, Danube, and Goeta (n—the length of time series tested, T—length of period tested, $W_r - T$—the test statistics according to Eq. (8) and (11), %—significance)

Neva	$n = 141$							
T	**28.2**	**6.41**	10.85	141*	12.82	4.86	20.14	7.83
W_rT	0.2590	0.1453	0.0981	0.0705	0.0704	0.0740	0.0550	0.0570
p-value	3.1×10^{-8}	0.0010	0.0516	0.4503	0.4836	0.3950	1.5996	1.4579
%	**99.999**	**99.89**	94.84	54.97	51.63	60.50	0.00	0.00
Neva	$n = 131$							
T	26.2	10.92	32.75	6.24	6.55	4.85	131*	8.19
W_rT	0.1847	0.1107	0.1158	0.1030	0.1018	0.0842	0.0830	0.0683
p-value	0.0001	0.0394	0.0305	0.0820	0.0971	0.3339	0.3863	1.0291
%	99.98	96.06	96.94	91.80	90.29	66.60	0.00	0.00
Neva	$n = 121$							
T	30.25	6.37	**11**	24.2	4.84	121*	8.07	5.76
W_rT	0.2008	0.1578	0.1282	0.1364	0.0896	0.0910	0.0851	0.0796
p-value	0.0001	0.0028	0.0233	0.0154	0.3209	0.3180	0.4857	0.7104
%	99.98	99.72	**97.66**	98.45	67.90	68.19	51.43	28.96
Danube	$n = 161$							
T	3.66	32.2	5.03	2.4	20.13	8.94	4.24	14.64
W_rT	0.0714	0.0689	0.0530	0.0524	0.0504	0.0506	0.0509	0.0524
p-value	0.23039	0.3011	1.1773	1.2865	1.5771	1.6118	1.6321	1.5111
%	76.961	69.89	0.00	0.00	0.00	0.00	0.00	0.00
Danube	$n = 151$							
T	21.5700	**3.6800**	**30.2000**	2.4000	5.0300	12.5800	8.8800	3.5100
W_rT	0.0776	0.0831	0.0786	0.0599	0.0611	0.0649	0.0604	0.0610
p-value	0.19	0.13	0.20	0.90	0.86	0.68	1.00	1.00
%	81.04	**86.88**	**81.88**	9.99	13.92	31.74	0.00	0.00
Danube	$n = 141$							
T	**20.14**	14.1	3.71	4.27	5.04	3.62	10.85	2.39
W_rT	0.0859	0.0708	0.0595	0.0618	0.0578	0.0605	0.0614	0.0654
p-value	0.1422	0.4675	1.1136	0.9926	1.3748	1.1937	1.1789	0.9493
%	**85.78**	53.25	0.00	0.74	0.00	0.00	0.00	5.07
Goeta	$n = 181$							
T	**30.17**	11.31	5.17	8.62	7.54	16.45	6.96	15.08
W_rT	0.0733	0.0665	0.0629	0.0623	0.0600	0.0568	0.0596	0.0565
p-value	0.102275	0.2089	0.3096	0.3436	0.4470	0.6243	0.5103	0.7036
%	**89.77**	79.11	69.04	65.64	55.30	37.57	48.97	29.64
Goeta	$n = 171$							
T	7.13	28.5	5.18	8.55	17.1	**11.4**	19	14.25
W_rT	0.0730	0.0628	0.0667	0.0657	0.0696	0.0727	0.0706	0.0694
p-value	0.1465	0.3860	0.2902	0.3332	0.2528	0.2055	0.2615	0.3057
%	85.35	61.40	70.98	66.68	74.72	**79.45**	73.85	69.43
Goeta	$n = 161$							
T	**7**	**5.19**	**14.64**	32.2	8.47	11.5	20.13	17.89
W_rT	0.0932	0.0765	0.0825	0.0705	0.0735	0.0741	0.0531	0.0513
p-value	0.0353	0.1587	0.1034	0.2984	0.2487	0.2509	1.3765	1.6477
%	**96.47**	**84.13**	**89.66**	70.16	75.13	74.91	0.00	0.00

* Denotes long-term trend

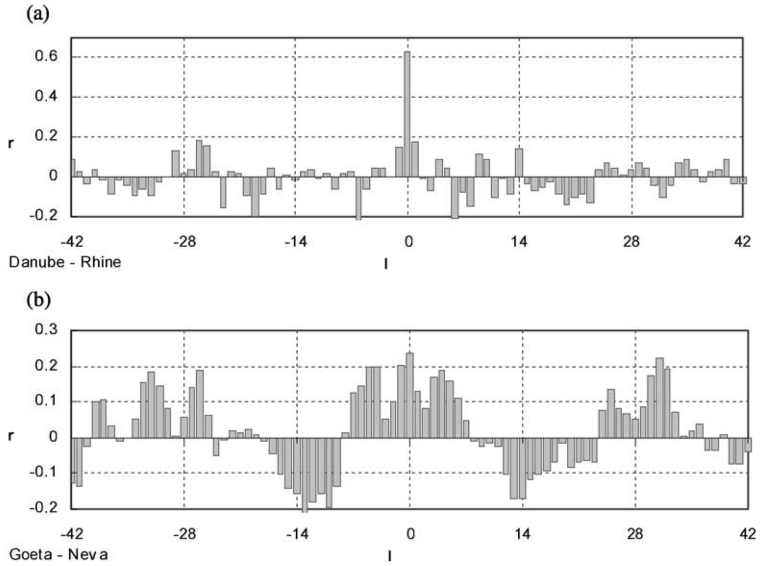

Fig. 8. (a) Cross-correlation of the mean annual runoff series (1860–1995) of Danube and Rhine (*r*-coefficient of correlation, *l*-shift in years), (b) Cross-correlation of the mean annual runoff series (1860–1990) of Goeta and Neva (*r*-coefficient of correlation, *l*-shift in years).

There is a direct relationship between the length of series and the length of the cycles, which can be identified by statistical analysis. To identify 28-year cycle we need at least 90–100 years data series.

Trends have not been detected for the large European river discharges. However, the cyclic behaviour between dry and wet periods are very clear.

Neither the trends of runoff decrease nor increase were found in long runoff series of the large European rivers. The cyclic occurrence of dry and wet periods was proved, however.

The temporal shift of the runoff extremes occurrence was identified by cross-correlation analysis. The dry and wet periods do not occur in the same years over the world, but their appearance is not random only.

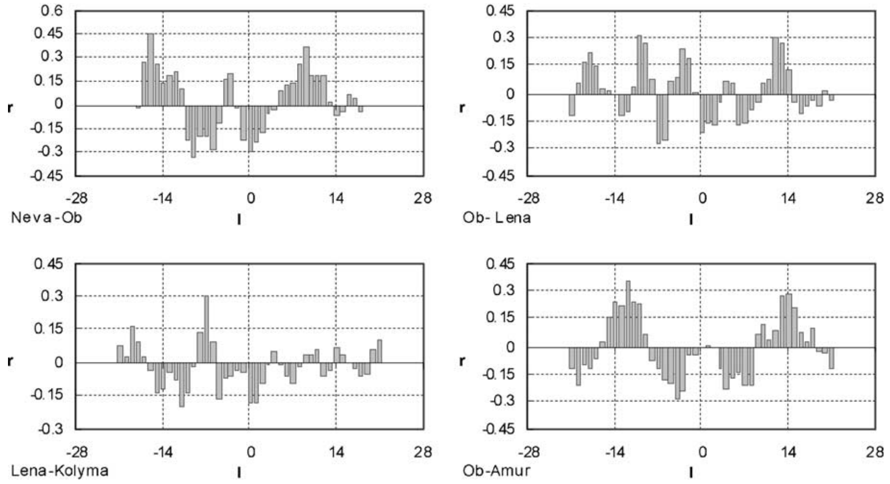

Fig. 9. Cross-correlation of the mean annual runoff series of Neva–Ob, Ob–Lena, Lena–Kolyma and Ob–Amur (*r*-coefficient of correlation, *l*-shift in years).

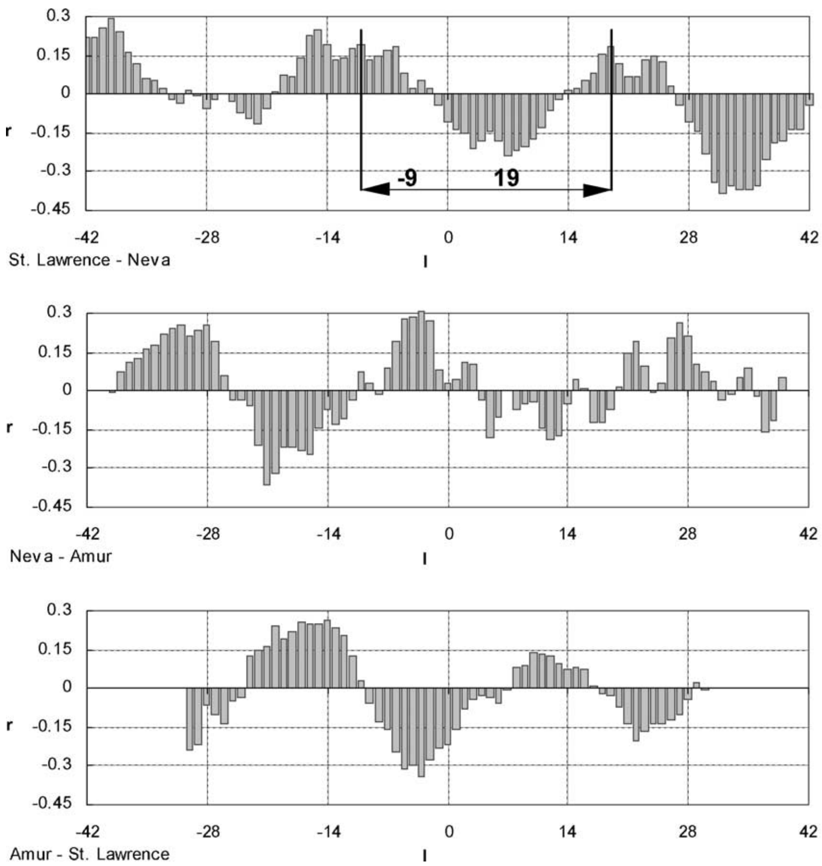

Fig. 10. Cross-correlation of the mean annual runoff series of Amur and St Lawrence (about 16 years), St Lawrence and Neva (about nine years), Neva and Amur (about four years), (*r*-coefficient of correlation, *l*-shift in years).

The trend analysis and the analysis of periodicity of the available long discharge series show the following:

- The trend analysis of the long discharge time series (more than 180 years) of the large West/Central European rivers (Goeta, Rhine, Neman, Loire, Wesaer, Danube, Elbe, Oder, Vistule, Rhone, and Po) shows no significant trend of the annual mean river discharge. In south–eastern European Rivers (Dniepr, Don, and Volga) decrease of runoff was found during 1881–1990.
- If we want to identify any trend uninfluenced by the 28-year periodicity of the discharge time series, we must determine the trend during a closed multiple loop both, starting and terminating by either minima (e.g. 1861–1946 in Central Europe) or maxima (e.g. 1847–1930 or 1931–1984 in Central Europe). Trends determined for other periods are influenced by the periodicity of the series and depend on the position of the starting point on the increasing or recession curve.
- If we want to compare the regime characteristics of the shorter periods (e.g. 10 years), we must select for the comparison such a period in the past that corresponds to the same phase of the cycle (with time shift of about 28 years). Significant change in discharge characteristics found by such analysis can be related to climate change. Nevertheless, we must take into account the existence of longer cycles that were not found yet because of the length of the available discharge series (Klige et al. 1989).

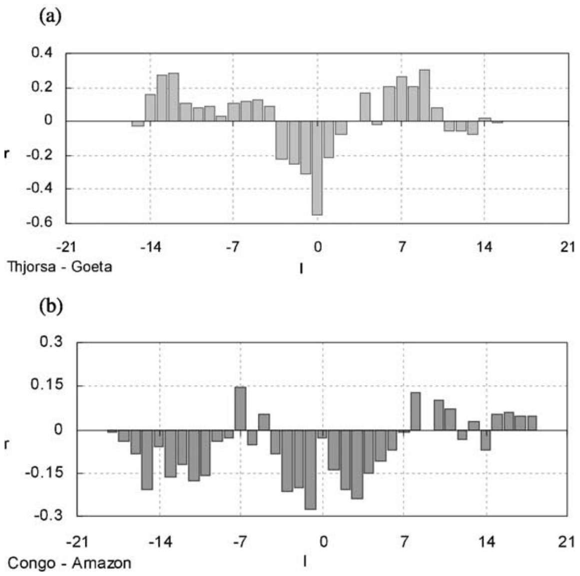

Fig. 11. (a) Cross-correlation of the mean annual runoff series (1947–1993) of Thjorsa and Goeta (*r*—coefficient of correlation, *l*—shift in years). (b) Cross-correlation of the mean annual runoff series of Congo and Amazon (*r*—coefficient of correlation, *l*—shift in years).

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