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Riverine water inflows and the Baltic Sea water volume 1901–1990

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Abstract

An analysis of riverine outflow into the Baltic Sea is presented for the years 1901–1990. The monthly outflows were calculated from the measurements in a number of representative rivers. The analysis included estimation of seasonal and multi-year characteristics of riverine outflows and periodic structure, as well as stochastic and statistical indicators characterising the influence of riverine water on the variability of the sea level and water volume in the basin. The article presents prognostic characteristics determined using analysis of parametric stochastic processes. The results obtained are related to oceanographic characteristics of the Baltic Sea.

Keywords: Baltic volume; Baltic balance; river outflow; river seasonality

Introduction

While the drainage area of the Baltic Sea covers more than 1.7 million km^2, the surface of the Baltic itself is four times smaller. This relation immediately suggests that fluctuations in the water conditions in the drainage area could influence the water balance in a semi-enclosed basin such as the Baltic Sea. Hydrological studies of the Baltic Sea and its drainage area embrace a long tradition, with data time series frequently extending over 100 years. Despite the numerous publications, the question of riverine inflow volume into the Baltic Sea is still an open one, as has been pointed out by several authors (Mikulski, 1986; Bergström and Carlsson, 1993; Cyberski, 1995).

The results obtained hitherto have suggested the possible influence of variations in riverine outflow on certain physical and chemical characteristics of Baltic Sea water. Cyberski (1995) confirmed the hypothesis that there is a distinct relationship between the variability of aspects of the water balance and salinity in the Baltic Sea. It is also very probable that there are connections between changes in the water conditions in the drainage area and other seawater parameters, e.g. the silicate content, particularly in the northern regions of the Baltic (Cyberski, 1998).

The aim of the present project was to analyse riverine outflow into the Baltic Sea during the period 1901–1990 and its impact on the variability of the mean sea level and water volume in the basin. The article presents the fundamental statistical and stochastic characteristics of this riverine outflow. The calculations were based on a 90-year data series of the monthly outflow of rivers from the Baltic Sea drainage area; the outflow figures were taken from specific hydrometric profiles. The mean sea level in the Baltic Sea basin was computed from the data of the Stockholm station, regarded as representative of the entire Baltic (Wróblewski, 1998a).

Field data and methods of analysis of the riverine outflow and sea level

Calculations of riverine outflow to the Baltic Sea were based on data series from 17 rivers (Fig. 1, Table 1). The rivers had been selected originally for an evaluation of the Baltic Sea water balance (Mikulski, 1986). They are considered representative of the Baltic Sea catchment area and this representativeness, though admitted *a priori*, has been demonstrated to a considerable degree in recent studies, especially by Bergström and Carlsson (1994) and Cyberski (1995). In the present project, the calculations used the following data from the period 1901–1990:

- results in the corrected data series from 17 rivers from the period 1921–1975 (Mikulski, 1986);
- data from the period 1976–1990 based on corrected hydrometric results from 17 rivers supplied by

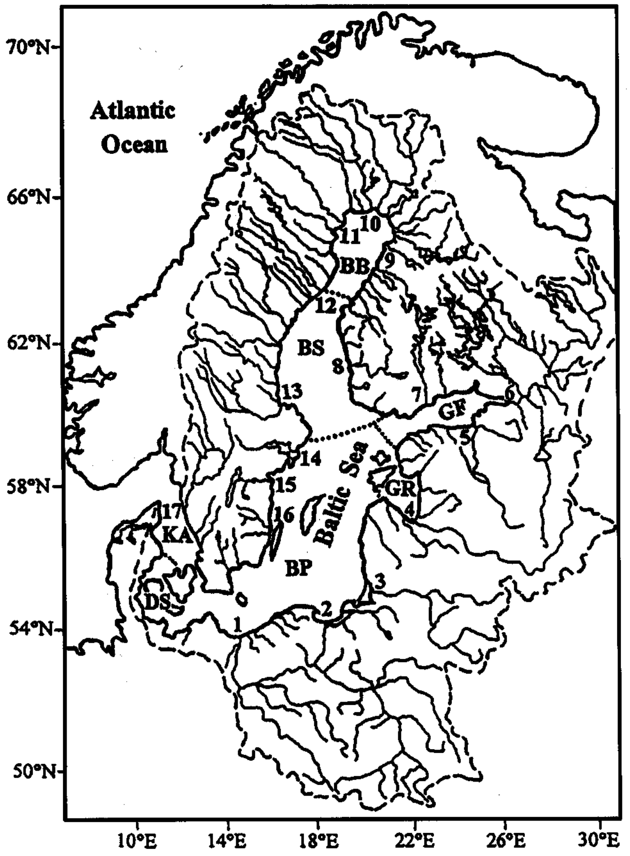

Fig. 1. *Drainage area of the Baltic Sea; the borders of the assigned balance regions have been marked Abbreviations: BB – Bothnian Bay, BS – Bothnian Sea, GF – Gulf of Finland, GR – Gulf of Riga, BP – Baltic Proper, DS – Danish Straits, KA – Kattegat. The numbers in the figure refer to selected drainage basins as in Tables 1 and 3.*

hydrological and hydrological-meteorological institutes in Finland, Poland, Sweden and Russia;

- supplemented and corrected historical hydrometric results on riverine outflow from 17 rivers from 1901–1920. Complete information regarding water outflow between 1901–1920 was available for 12 rivers. Outflow values for the relevant (or shorter) period in the other five rivers were reconstructed using statistical methods (Cyberski, 1995) based on 70-year data series from the 17 rivers (1921–1990). The correlations and regression formulae obtained for the monthly outflow from the 5 missing rivers are presented in Table 2.

The variations in riverine outflow were analysed using Pearson's correlation coefficient and Spearman's non-parametric rank test. The statistical significance of the regression slope coefficient (directional vector) was examined by Student's t-test. As in climatological analysis, the difference between trend and tendency was distinguished. In accordance with Semenov and Alekseeva (1989), a trend was assumed when $p_\alpha \leq 0.05$ and $a \geq 2S_a$, and a tendency when $0.25 \geq p_\alpha > 0.05$ and $a \geq S_a$, where p_α is the statistical significance level of the slope regression coefficient a, and S_a the estimated error.

The calculation of the mean monthly sea level in the Baltic Sea (MMSLB) is of fundamental importance in any analysis of the water balance in this basin. The surface area of the Baltic, excluding the Kattegat, is 392 000 km^2 (Ehlin and Mattisson, 1976). This means that a 1 cm variation in the mean level of the Baltic Sea leads to a change in water volume of 3.92 km^3. Nevertheless, any computation of mean Baltic Sea level variations from monthly means derived from tide-gauge readings is still a complicated matter. The problem consists in determining a common level for all tide gauges, because of the extremely long shoreline of several thousand kilometres, and the vertical motions of the Earth's crust in the region. The northern shores of the Baltic Sea, in Sweden and Finland, are being uplifted at a rate of several cm per year, while in the southern regions, depression of shorelines has been observed locally.

Further problems arise through differences in reference levelling in particular Baltic countries. Because of these difficulties, only one time series of mean monthly sea levels has been published that takes into account data from multiple tide gauges for the period 1901–1940 (Lazarenko, 1965). Calculations of mean sea level were discontinued because of the problems in resolving levelling relations and the termination of measurements during the Second World War. The difficulties in evaluating mean monthly sea levels were overcome after the introduction of empirical orthogonal functions (EOF), calculated from six tide gauges, followed by their linkage through regression equations with MMSLB values calculated geodetically by Lazarenko. In the present project, MMSLB values were subsequently calculated from EOF determined from tide-gauge readings at six stations between 1896 and 1986 and established regression relations (Wróblewski, 1992, 1998a). Simultaneously, the mean sea level of the Baltic Sea was calculated on the basis of the Stockholm tide gauge data for the same time interval. The 1901–1940 data from both time series were selected and compared with Lazarenko's MMSLB series. The RMS error between the Lazarenko series and the calculated mean sea levels was 1.8 cm in the case of the EOF data and 1.9 cm in the series calculated from the Stockholm tide-gauge readings. The RMS error of the MMSLB series calculated from the Stockholm tide-gauge readings and that evaluated from EOF for the years 1896–1986 was 1.9 cm.

Because the 1901–1990 data are accessible, the mean sea levels in the basin were calculated on the basis of a cyclostationary series of readings from the Stockholm tide gauge (Spencer and Woodworth, 1993), despite the fact that these data are slightly less accurate as compared with the EOF series and that slight differences exist between the two series as regards the amplitudes of the periodic structure (Wróblewski, 1998a). Even so, the Stockholm tide gauge is assumed to be representative of the Baltic basin as regards single observations, due to its specific location in the vicinity

Table 1. Characterisation of rivers from the Baltic Sea catchment area included in the study

River	River number	Hydrometric profile	Area of drainage basin [km^2]	Observation period
Alsteran	16	Getebro	1345	1920–1990
Dalälven	13	Fäggeby	25037	1852–1975
		Langhag	25037	1976–1990
Daugava	4	Daugavpils	64500	1881–1990*
Gota älv	17	Vänern	46830	1807–1975
		Vargöns krv	46830	1976–1990
Kalajoki	9	Hihnalankoski	3025	1921–1975
		Niskakoski	3005	1976–1990
Kemijoki	10	Taivalkoski	50820	1911–1975
		Isohara	50900	1976–1990
Kokemäenjoki	8	Harjavalta	26030	1921–1990
Kymijoki	7	Pernoo	36535	1900–1975
		Piirteenvirta	36535	1976–1990
Luleälven	11	Bodens krv	24488	1900–1990
Malaren-Norrström	14	Övre-Stockholm	22600	1901–1990
Motalaström	15	Vättern	6359	1858–1975
		Roxen	13243	1873–1975
		Kimstad	13243	1976–1990
Narva	5	Narva	56200	1881–1990*
Neva	6	Novosaratovka	281000	1859–1990*
Neman	3	Smalininkai	81200	1812–1990*
Odra	1	Gozdowice	109729	1901–1990
Umeälven	12	Umea	26499	1919–1975
		Stornorrfors krv	26499	1976–1990
Vistula	2	Tczew	194376	1901–1990

*With brief interruptions.

Table 2. Regression formulae of the monthly discharge (m^3 sec^{-1}) from selected rivers

Measurement station	Period	Regression equation and characteristic data
Kemijoki	01.1901–12.1910	$Q_{Kem} = 120.5 + 0.96{*}Q_{Dalälven} + 0{,}62{*}Q_{Luleälven\ (-1\ lag)}$ $N = 960$, $R^2 = 0.625$, $p_\alpha < 0.001$
Kalajoki	01.1901–12.1920	$Q_{Kal} = 2.04 + 0.048{*}Q_{Kemijoki\ (-1\ Lag)}$ $N = 840$, $R = 0.885$, $p_\alpha < 0.001$
Kokemäenjoki	01.1901–12.1920	$Q_{Kok} = 2.4 + 0.69{*}Q_{Kymijoki(-1\ Lag)}$ $N = 840$, $R = 0.979$, $p_\alpha < 0.001$
Umeälven	01.1901–12.1918	$Q_{Ume} = 9.9 + 0.85{*}Q_{Lulealven(-1\ Lag)}$ $N = 840$, $R = 0.859$, $p_\alpha < 0.001$
Alsteran	01.1901–12.1919	$Q_{Als} = -0.24 + 0.73{*}Q_{Eman}$ $N = 840$, $R = 0.796$, $p_\alpha < 0.001$

R^2 multiple correlation coefficient; R correlation coefficient; N data number.

Table 3. Mean annual riverine outflow into the Baltic Sea [m^3·s^{-1}; km^3·a^{-1}]

Mean value [m^3·s; km^3/year]		
1921–1975	1950–1990	1901–1990
After Mikulski (1982)	After Bergström & Carlsson (1994)	After Cyberski (1995)
14895	15310	15215
470	483	480 (*437)

* without Kattegat sub-basin.

of the node of single-node seiches in the Bothnian Bay – Danish Straits and the Gulf of Finland – Danish Straits system. The mean monthly variations of water volume (MMWVB) in the Baltic Sea were calculated from the MMSLB series, assuming the relation between sea level changes and water volume as given earlier.

Outflow description

Over 200 rivers discharge into the Baltic Sea; being unevenly distributed around the periphery of the sea, these rivers are characterised by distinctly differing outflows. More than 100 of these rivers enter the sea from Scandinavia; the southern and south-eastern shores of the Baltic are less abundant in watercourses. The majority of watercourses in the catchment area are small ones. Of 102 rivers with a mean annual flow intensity of >10 m^3·s^{-1}, the flow rates of 50 are <25 m^3·s^{-1}. The Neva, Vistula, Daugava, Neman, Odra, Gota älv, Kemijoki and Luleälven discharge the greatest volumes of water into the Baltic. Only 32 rivers bring in more than 50 m^3·s^{-1}, and of these, only 27 have flow rates of >100 m^3·s^{-1}.

The mean riverine outflow into the Baltic during the period 1901–1990 is listed in Table 3. Generally, these values do not differ significantly from those published by Mikulski (1986) or Bergström and Carlsson (1994) the differences do not exceed several percent, even though the latter authors analysed a slightly different set of rivers in their calculations. When the mean values from 1921–1975 and 1950–1990 were compared with the data from a longer time interval 1901–1990, these data were found to be statistically identical.

Coefficients of variation of riverine outflow obtained in the analysis of the annual outflows (Table 4) fell within the range 0.118–0.362 (the Luleälven and Daugava). No distinct regional differences were found, and the coefficient of variation did not exceed 0.25 in catchment areas with many lakes. Of 17 rivers examined, no statistically significant variations were manifested as a trend or tendency in the outflow of 2/3 of them. A time trend was apparent in only two cases–both negative vectors, in the Daugava and Neman; a tendency was found in three cases–two negative vectors (the Neva and Narva) and a positive vector in the

Table 4. Variation and regression coefficients of the annual riverine outflow in the Baltic Sea drainage basin (Cyberski, 1995)

Drainage Basin	No.	River	Period	C_v	Regression slope coefficient	Trend line or Tendency
Bothnian Bay	9	Kalajoki	1921–1990	0.317	0.005	Statistically insignificant
	10	Kemijoki	1911–1990	0.191	0.487	Statistically insignificant
	11	Luleälven	1901–1990	0.118	−0.255	Statistically insignificant
Bothnian Sea	13	Dalälven	1901–1990	0.225	−0.174	Statistically insignificant
	8	Kokemäenjoki	1921–1990	0.299	0.460	Tendency ($p_\alpha = 0.239$)
	12	Umeälven	1919–1990	0.153	−0.266	Statistically insignificant
Gulf of Finland	7	Kymijoki	1901–1990	0.266	0.142	Statistically insignificant
	6	Neva	1901–1990	0.228	−2.892	Tendency ($p_\alpha = 0.218$)
	5	Narva	1921–1990	0.282	−1.233	Tendency ($p_\alpha = 0.056$)
Gulf of Riga	4	Daugava	1901–1990	0.362	**−2,328**	**Trend line ($p_\alpha = 0.005$)**
	16	Alsteran	1920–1990	0.317	−0.003	Statistically insignificant
	14	Malaren-Norrström	1901–1990	0.305	−0.135	Statistically insignificant
Baltic Proper	15	Motalaström	1901–1990	0.306	−0.105	Statistically insignificant
	3	Neman	1901–1990	0.173	**−0.816**	**Trend line ($p_\alpha = 0.0425$)**
	1	Odra	1901–1990	0.253	0.296	Statistically insignificant
	2	Vistula	1901–1990	0.223	0.985	Statistically insignificant
Danish Straits & Kattegat	17	Göta älv	1901–1990	0.225	0.198	Statistically insignificant
Baltic Sea		Total riverine outflow	1901–1990	0.106	−5.170	Statistically insignificant

Table 5. Correlation coefficient of the outflow of selected rivers from the drainage area of the Baltic Sea *versus* total riverine inflow into the Baltic Sea. (Calculations for annual outflow values from the period 1901–1990)

River	Profile	Correlation coefficient
Alsteran	Getebro	0.461***
Dalälven	Langhag	0.696***
Daugava	Daugavpils	0.595***
Gota älv	Vänern	0.631***
Kalajoki	Hihnalankoski	0.574***
Kemijoki	Taivalkoski	0.529***
Kokemäenjoki	Harjavalta	0.769***
Kymijoki	Pernoo	**0.826*** **
Luleälven	Bodens krv	0.199*
Malaren-Norrström	Övre-Stockholm	0.724***
Motalaström	Kimstad	0.598***
Narva	Narva	0.714***
Neva	Novosaratovka	0.653***
Neman	Smalininkai	0.504***
Odra	Gozdowice	**0.182***
Umeälven	Stornorrfors krv	0.510***
Vistula	Tczew	0.269**

Correlation coefficient statistically significant at p_σ * ≤ 0.1; ** ≤ 0.01; *** ≤ 0.001; numbers in bold represent extreme values of the correlation coefficient.

Kokemäenjoki. Slope regression coefficients were found to be negative in river outflows situated close to one another; in the catchment areas of the Neman, Daugava, Narva and Neva, this observation suggests a phenomenon of considerable territorial extent.

The total annual riverine outflow into the Baltic Sea between 1901–1990 is characterised by a relatively regular frequency distribution, well depicted by the Gaussian distribution (Fig. 2), with the dominant coming within the 450–500 $km^3 \cdot a^{-1}$ range. The monthly riverine outflow values from the same period, in turn, fit the natural logarithm distribution well, the dominant lying in the 30–35 $km^3 \cdot month^{-1}$ range, and the mean monthly rising to 40 km^3 (Fig. 3).

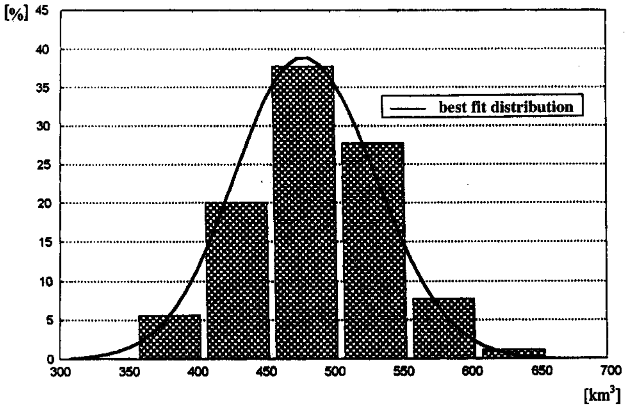

Fig. 2. *The normal distribution of annual outflows of riverine water into the Baltic Sea.*

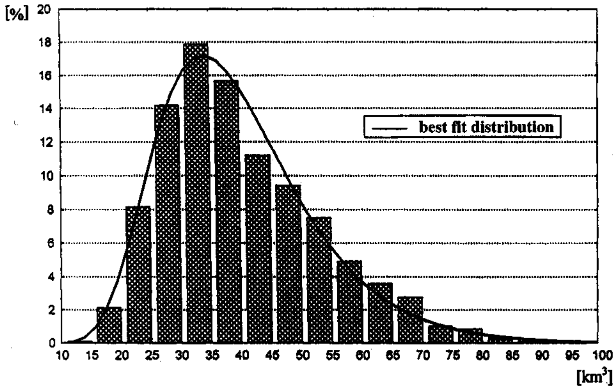

Fig. 3. *The log-normal distribution of monthly riverine outflow into the Baltic Sea.*

In general, the weak variations in C_v as well as the limited vector values of the annual outflows were found to be statistically insignificant in most cases (Table 4). However, the correlation of the outflow of each of the 17 rivers examined with the total riverine outflow is statistically highly significant, with $p_\alpha < 0.001$ in 14 cases and $p_\alpha \leq 0.01$ in one case (Vistula). Only in two cases–the Odra and Luleälven–was the correlation weak ($p_\alpha \leq 0.1$) (Table 5). The following hypothesis could thus be formulated: the hydrological system of the Baltic Sea catchment area is characterised by a relatively stable order of riverine inflow (Cyberski, 1995).

An important issue relevant to the long-term changes in riverine outflow was the determination of general tendencies observed during the period 1901–1990. This problem was overcome by calculating not only annual outflows but also monthly and seasonal values in each year. These data were analysed by the same methods as were the annual outflows. This approach was supported by the results of earlier studies (Cyberski 1995), which showed that in the 20th century very significant changes have occurred in the seasonality of the annual riverine outflow.

During the analysed period, seasonal variations were very different, even though annual outflows were almost unchanged (Table 6). Generally speaking, noticeable changes have occurred in the annual seasonality of outflows into the Baltic over a little less than a century, and especially in the 20 years from 1970 to 1990. The spring outflow has increased by 13%, the summer outflow has decreased by around 28%, and the winter outflow has risen by nearly

Table 6. The trend in river discharge from the Baltic Sea catchment area during 1901–1990; statistically significant figures are underlined bold (Cyberski, 1995)

Year (Jan-Dec) Annual trend $m^3 s^{-1}$	Spring (Mar-May) Quarterly trend $m^3 s^{-1}$	Summer (Jun-Aug) Quarterly trend $m^3 s^{-1}$	Autumn (Sept-Nov) Quarterly trend $m^3 s^{-1}$	Winter (Dec-Feb) Quarterly trend $m^3 s^{-1}$
−5.5	**23.9**	−**72.5**	−8.7	**32.2**

30%, while the figures for autumn and the entire year have remained practically unaltered.

Periodic structure of the riverine outflow into the baltic sea

The calculations were performed on the data series of the monthly and annual riverine outflows into the Baltic Sea. The analysed series of monthly outflows is not homogenous with respect to the rivers in Sweden and Finland because dam construction has altered the seasonality of river flows in these countries. For this reason, the data series can be regarded as consistent for the entire basin for the period 1901–1970. The periodic structure of the outflows was evaluated for 1901–1990; the corresponding values for the 1901–1970 observations were also computed. The amplitudes of the periodic oscillations were calculated using the Finite Fourier Transform. The statistical significance of the amplitudes was examined using the bootstrap method, which was introduced at the beginning of the 1980s (Efron and Gong, 1983).

This method allowed a general population to be constructed from the existing random sample and the empirical distribution function of this population $f(\Theta)$ to be calculated. From this, the significance of the data in the series Θ could be determined. The results of the calculations, i.e. the amplitudes of the riverine outflows (MRO) and the levels of their statistical significance, are illustrated in Fig. 4. The analysis showed the declining amplitudes of harmonic components to be a characteristic feature of the monthly riverine outflows. In the presentation of seasonal oscillations of the outflow volumes between 1901–1990, the data from the period 1901–1970 were added in square brackets. The following parameters were found to be statistically significant at the 5% level: the annual period (12.9 [14.2] km^3, variance 46.5%), the six-month period (8.1 [8.4] km^3, variance 18.3%) and the 4-month period (2.5 [2.3] km^3, variance 1.7%). In short, 66.5% of MRO variance could be described by statistically significant oscillations. As regards long-term variability of these amplitudes, the calculations of the annual period produced results that were very different in the five time series. More details concerning the long-term variability of the periodic structure are given in Table 7. After 1970, there was a marked decrease in the annual period amplitude as compared with the earlier time intervals. However, it is hard to provide a definitive interpretation of the observed changes in other periods of oscillations.

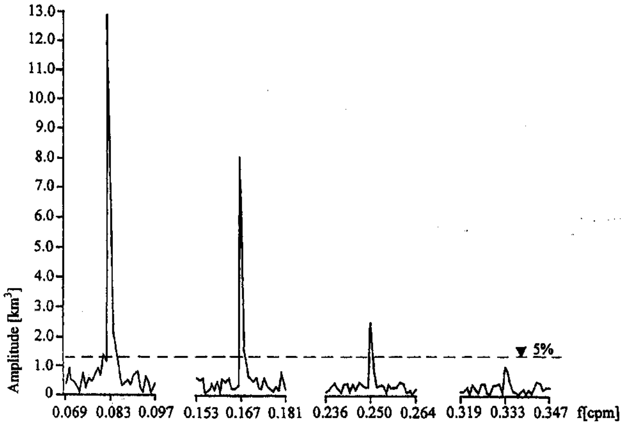

Fig. 4. *The amplitude spectrum of monthly riverine outflows into the Baltic Sea; calculations for the period 1901–1990.*

The annual and six-month periods are related to the respective solar tides in the atmosphere and can be detected in a number of meteorological phenomena. The 4-month period, a harmonic component of the annual period, was also discernible in meteorological fields. Thus, it is clear that the calculated periodic structure of the outflows is related to atmospheric precipitation within the Baltic Sea drainage area. When taking into account the vast expanse of the drainage area and the considerable variability in precipitation within the drainage areas of individual rivers, the harmonic regularity of MRO periodic structure is a highly unexpected finding.

The amplitudes of annual outflow fluctuations were calculated in accordance with the method applied for MRO and the results are shown in Fig. 5. At the 5% confidence level, the following parameters were statistically significant: the amplitudes of the ~90-year (18.7 km^3, variance 8.0%), ~30-year (30.1 km^3, variance 21.0%) and 4.3-year oscillations (18.1 km^3, variance 7.5%). The oscillations of the 90-year period can not be interpreted because of the insufficient resolution of the calculations within the assumed time span. A significant influence could be assigned here to the changes

Table 7. Variations in the amplitudes of seasonal fluctuations in riverine outflow into the Baltic Sea between 1901 and 1990

Measurement period	Sa* [km^3]	Ssa** [km^3]	4 months [km^3]	3 months [km^3]
1901–1918	15.211	5.893	0.859	1.583
1919–1936	14.546	9.877	2.778	1.501
1937–1954	13.718	8.690	2.176	0.320
1955–1972	13.247	9.083	3.767	1.983
1973–1990	8.813	7.353	3.292	2.118

* solar annual tide; ** solar semiannual tide.

in riverine outflow recorded in the second half of the twentieth century. Within MRO, an increase in outflow volume took place between 1971 and 1990, with a linear approximation of 0.35 ± 0.12 km^3·a^{-1}. Another unexpected result of the analysis is the strongly marked 30-year period. Although the determination of this period shows rather low resolution, the oscillations are characterised by an exceptionally high variance, considering that they are derived from the annual data series. A period of similar length was discovered in the oscillations of the Earth's pole; a 24-year period (Markowitz, 1960) with an amplitude of *ca* 0.02″, later corrected to 31 years (Dickman, 1981) and then to 27.5 years duration (Vondrak, 1985). There is no interpretation of the sources generating this 30-year period in the riverine outflow, and hence in atmospheric precipitation, it requires additional studies.

The effect of river outflow on the variability of the water mass in the Baltic Sea

To assess the influence of MRO on MMSLB fluctuations, the data on daily flows through the Danish Straits should be analysed. However, the available data time series are not long enough. The mean monthly values introduced in this study and hitherto applied in evaluations of the water balance in the Baltic Sea basin, e.g. Jacobsen (1986) display too strong a low-pass filtration. This strong filtration effect is caused by the character of the forcing in the basin exerted on the daily sea levels. These values are the basis for MMSLB calculations and depend mainly on the flows in the Danish Straits.

The sea levels used in the subsequent calculations of volume changes can be found in the literature. Between 1926 and 1935, the fluctuations of the daily filling of the Baltic Sea lay within the 3.9–11.8 km^3 range, the maximum reaching 39.2 km^3 (Hela, 1994). The corresponding calculations in the Pilot Study Year 1975–1976 produced a mean value of 7.8 km^3. On 27–28 December 1976, the daily increase in volume of the Baltic Sea amounted to 30.5 km^3 (Lazarenko, 1986). The daily mean riverine outflows in particular months fit into the 0.7–2.0 km^3·day^{-1} range (see Table 8); water mass increments are always positive. The increments due to water exchange with the North Sea appear to be more dynamic with positive as well as negative values.

The maximum daily increase in water volume in the Baltic Sea within the period 1926–1935, i.e. 39.2 km^3, was much greater than many of the monthly riverine outflows given in Table 9. During the Pilot Study Year, the measurements taken on 2 days resulted in an increment of 30.5 km^3. This was also greater than the monthly MRO outflow during winter. Table 9 contains comparison of the riverine outflows and flows through the Danish Straits.

The impact of riverine water on the Baltic Sea was further analysed by calculating the coherence of MRO and MMSLB in the period 1901–1990 (the total number of data–1080). The squared coherence was applied together with the Finite Fourier Transform. Ensemble averaging and overlapping was also carried out. The results of these calculations are shown in Fig. 6. The results indicate that for frequencies corresponding to Sa and Ssa, and for frequencies <0.028 cpm and those close to 0.5 cpm, the coherence is statistically significant at the 0.01 level. However, the interpretation of the results requires the inclusion of basic relationships ensuing from the forcing in

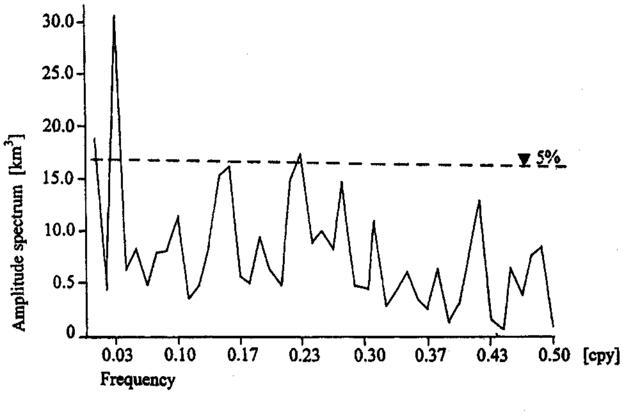

Fig. 5. *The amplitude spectrum of mean annual riverine outflows into the Baltic Sea; calculations for the period 1901–1990.*

Table 8. Monthly and daily mean riverine outflow into the Baltic Sea between 1901 and 1990 (Cyberski, 1995)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Riverine water outflow km^3/month	25.4	22.9	30.0	44.7	60.7	53.9	42.6	36.8	33.2	34.3	32.0	20.3
Mean daily outflow per month km^3/24h	0.8	0.8	1.0	1.5	2.0	1.8	1.4	1.2	1.1	1.1	1.1	0.7

MMSLB. The effect of the annual period is one of the important factors to be accounted for. In this case, the coherence phase amounts to $-140°$ there are degrees and corresponds to the time difference of the annual culmination in both data time series. For comparison, the phases of the annual period, calculated from the mean monthly sea levels, are identical ($-62°$) in the Baltic Sea basin and in the North Sea (Wróblewski, 1998b).

Thus, it can be concluded that the coherence values obtained are the calculated result of the effect of the appearance of the annual period in both data time series. Phase displacement indicates that substantial forcing by riverine outflow in the annual period of MMSLB is lacking. A similar analysis can be performed for the six-month period: the results point to a lack of effective forcing in this case too. For long-term periods with frequencies < 0.028 cpm, the phase comes close to zero. Nevertheless, the data time series analysed are still too short to discover whether the significant coherence is a direct effect of the riverine water, or whether it is more a result of the macroscale atmospheric processes influencing both data time series through a complicated system of collinearities. In the case of oscillations near the frequency of 0.5 cpm, where the phase is close to zero, the coherence indicates the need for calculations using data with a smaller time step. It has already been established from measurements that the real impact of riverine outflow becomes apparent when a small volume of water flows through the Danish Straits. Hence, the analysis of coherence does not allow the establishment of an unequivocal link between MMSLB and MRO, because the periods appearing in the latter can be also found in many collinear hydro-meterological phenomena. The results of measurements from 1976 (Table 9) are a good illustration of conditions forcing changes in the water volume of the Baltic Sea: the data on monthly riverine outflows are listed against the respective flows through the Danish Straits.

The analysis of coherence can be supplemented by an evaluation of correlations. Following recent publications, the mean level of the North Sea appears to be the main factor forcing changes in the Baltic water volume (Wróblewski, 1998b), together with the well-known zonal circulation in the Danish Straits region. The relevant correlation coefficients were calculated for the period 1928–1970 (data description in the mentioned publication) with MRO admitted as the third forcing factor. Longer data time series were not available because of the limited possibilities of calculating the mean sea level of the North Sea. The correlation coefficients were obtained in the earlier given sequence of exciting forces 0.72, 0.66 and–0.02. Next, in the same order, partial correlation coefficients were calculated which illustrate the isolated influence of each forcing factor. The results obtained are 0.53, 0.40 and 0.08.

These calculations demonstrated that MMRO exerted only a slight effect on the variability of the mean monthly water volume changes in the Baltic Sea. This is due to the fact that the other two forces display a much greater dynamic influence and, in comparison with them, the relatively stable riverine outflows, which carry relatively small water volumes, do not bring about significant changes in the time series of water mass in the basin. As has already been mentioned, the seasonality of both data series displays considerable phase displacement, and the stochastic component of the fluctuations is of particular importance in the MMSLB series. It is evident that the basic variability of water mass in the Baltic Sea is caused by barotropic flows through the Danish Straits forced by the local zonal

Table 9. Monthly flows through the Danish Straits determined for particular months in 1976 (Jacobsen, 1986) and the respective riverine outflows into the Baltic Sea (Cyberski, 1995)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Monthly flows through the Straits km^3/month	120.6	90.6	9.4	62.3	98.3	−56.5	2.8	140.1	56.9	−31.4	−169.6	92.0
Monthly outflows of riverine waters into the Baltic km^3/month	27.0	24.1	27.2	37.8	49.1	34.7	26.0	25.4	22.7	22.6	23.3	24.0

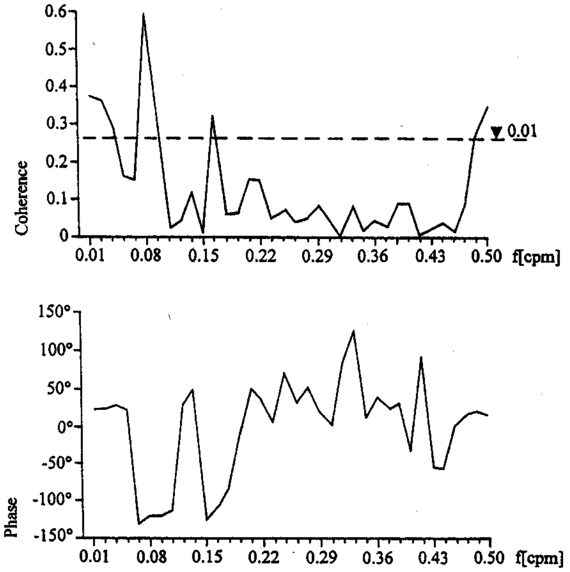

Fig. 6. *Squared coherence of monthly riverine outflows and mean monthly oscillations of the water volume in the Baltic Sea; calculations for the period 1901–1990.*

circulation in the Danish Straits and surrounding areas, as well as by the mean sea level of the North Sea. This, in turn, is under the influence of the macroscale atmospheric fields over the North Atlantic and the complicated conditions in the stratified ocean (Druet, 1994).

However, the continuous input of freshwater into the Baltic Sea, during the weak exchange through the Danish Straits, appears to be the major factor influencing two-layer flows in this region. The mean baroclinic flow, linked as it is to the positive water balance in the Baltic Sea, is directed towards the North Sea because of the discharge of riverine water. Atmospheric precipitation plays a smaller role and is nearly balanced out by evaporation (Omstedt, 1997). The weak flow dynamics, appearing temporarily in the Danish Straits, amplifies the effects of the relatively stable and, with regard to the water mass increment, the always positive, riverine water outflow. This outflow has important influence on the physico-chemical parameters of the Baltic water. The river water effect is not compensated by salt-water inflows from the North Sea. As a result, the water in the Baltic Sea is much less saline than that of the North Sea. The differences in salinity are an important factor in the dynamics of a stratified water mass in the basin (Jankowski, 1983).

Parametric stochastic processes

Bearing in mind that 66.5% of the data series variance is determined solely by three significant amplitudes, the application of parametric stochastic processes to Baltic volume simulation and prognosis requires closer examination. Statistical predictability can be determined by autoregression parameters, which belong to the general characteristics of the phenomenon under investigation. Owing to the change in the seasonality of the riverine outflow into the Baltic Sea, the efficiency of the parameters evaluated for the 90-year data series was tested by calculations conducted for the period 1971–1990. For this reason, the trend, which defines the increase in the riverine outflow volume and was discussed earlier, was removed from the 20-year data series. Both data series were then standardised by the incorporation of empirical seasonal characteristics. From every value of the series the proper monthly mean was substracted and the result was divided by monthly standard deviation. In the subsequent stage, the usefulness of ARMA(1,1), ARMA(2,1) and AR(p), p = 1–15, was tested. Autoregression parameters were calculated using the maximum likelihood method (Box and Jenkins, 1976). The initial choice of the process to be applied to standardised data series was based on an Akaike criterion. The results were verified by diagnostic computation of the forecast with a lead time of one time step. The results showed little difference between the effectiveness of specific AR(p) processes. This can be explained by the fact that prognostic calculations with standardised data series were of less importance than the effect of standardisation on the data

Table 10. Application of parametric stochastic processes AR(8) to forecast and simulate monthly riverine outflows into the Baltic Sea for the period 1901–1990.

Measurement period	river outflows σ [km^3]	MAE [km^3]	RMSE [km^3]	PER [km^3]	MAE/PER [%]
1901–1990	13.4	4.7	6.4	11.0	43.6
1971–1990 parameters for the period 1901–1990	10.9	4.6	6.2	9.9	46.5
1971–1990 parameters for the period 1971–1990	10.9	3.9	5.0	9.9	39.4

Legand: σ – standard deviation, MAE – mean absolute error of the unit time forecast, RMSE – root mean square error of the unit time forecast, PER – root mean square error of the unit persistence forecast.

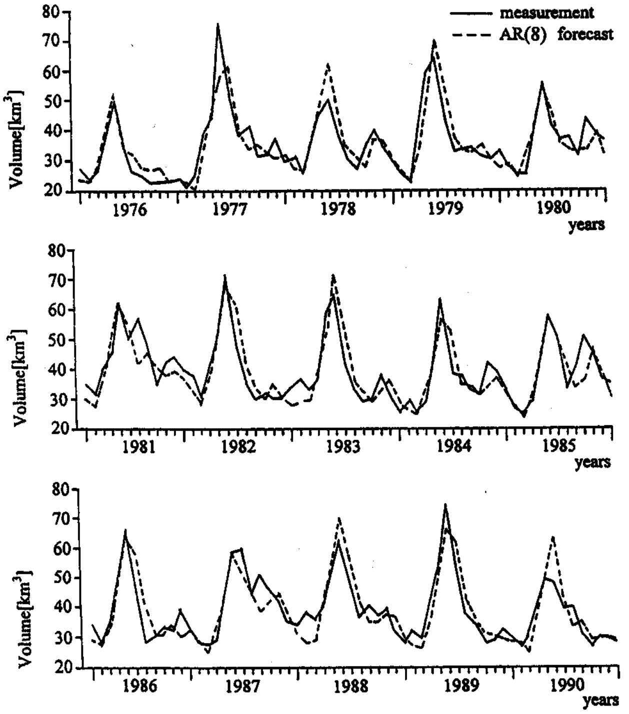

Fig. 7. *Application of the seasonal AR(8) process to forecast riverine outflow into the Baltic Sea with a lead time of one month; calculations for the period 1901–1990.*

series itself. Additionally, parameter φ is 0.58 in the equation AR(1) of the 90-year data series and 0.64 in the 20-year series, hence the effect of extremely small parameters of the higher order becomes negligible. The results of the calculations are shown in Table 10.

As the results listed in Table 10 indicate, the parameters of the AR(8) process, calculated on the basis of the 1901–1990 data series, can be applied to simulation and forecasting, despite the heterogeneity in the final data segment. The results of forecast parameter calculations on the basis of the 90-year data series, applied to the final years of the series examined, are illustrated in Fig. 7.

Summary

- Riverine outflow into the Baltic Sea between 1901–1990 was calculated on the basis of water-gauge measurements in 17 rivers. Data from 12 rivers were available for the years 1901–1920. The missing hydrometric data were supplemented from reliable regression calculations.
- Regression coefficients of the annual outflows calculated for 17 rivers did not indicate statistically significant tendencies in 12 cases; there was a negative tendency in 4 rivers and a positive one in 1 river. The calculated mean annual riverine outflow into the Baltic Sea amounted to 480 km^3·a^{-1} and was only slightly different from previously published values calculated for shorter measurement periods. The mean annual riverine outflow values calculated for a 40 and 90-year time series were nearly identical. No trend was distinguished in the analysed total riverine outflow into the Baltic Sea. The total annual riverine outflow was in most cases well correlated with the outflow of each of the 17 rivers, and the correlation significance level ranged from 0.01 to 0.001 with only one case falling to 0.1.
- Dam construction in Sweden and Finland has caused changes in seasonal distribution of riverine outflow, this having become conspicuous since the 1970s; nevertheless, the variability of the annual and autumn outflows has remained stable. In comparison with the period 1901–1970, the spring outflow has increased by 13%, the summer outflow has decreased by 28% and the winter outflow has risen by 30%.
- The periodic structure of monthly riverine outflows in 1901–1990, analysed at the 5% significance level, shows that an annual period (amplitude 12.9 km^3), a six-month period (amplitude 8.1 km^3) and a 4-month period (amplitude 2.5 km^3) occur. In general, it was found that significant periodic oscillations determine 66.5% of the riverine outflow variance. Within the same significance level, specific oscillations were distinguished with periods of ~90 years (amplitude 18.7 km^3 and lack of weak resolution of the calculation period), ~30 years (amplitude 30.1 km^3) and 4.3 years (amplitude 18.1 km^3). The generation of seasonal periodicity in hydrometeorological phenomena is well recognised and it is this that explains the variability of atmospheric precipitation responsible for the riverine flows. However, the explanation of multiyear periods needs further examination.
- The relatively stable riverine outflow into the Baltic Sea exerts a strong influence on the physico-chemical properties of Baltic waters, which are in fact classified as estuarine waters. As regards fluctuations of the mean monthly water volume in the Baltic, the effect of the North Sea sea level changes and zonal circulation over Danish Straits are dominant.
- The analysis has provided evidence that process AR(8) applied to seasonally standardised monthly riverine outflows can be used to simulate and forecast the data time series under scrutiny.

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