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BALTICA Volume 23 Number 1 June 2010 : 33-46

Long-term water balance of the Curonian Lagoon in the context of anthropogenic factors and climate change

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Jakimavičius, D., Kovalenkovienė, M., 2010. Long–term water balance of the Curonian Lagoon in the context of anthropogenic factors and climate change. *Baltica, 23 (1), 33-46.* Vilnius. ISSN 0067-3064.

Abstract The Curonian Lagoon has been extensively used by the activities of the Klaipėda State Seaport. Presently there is concern about the impact of climate change on physical geographical factors. The question is what impact climate change and port modernization projects had on the hydrological regime of the Curonian Lagoon. For this reason the water balance of the Curonian Lagoon was calculated for the period of 1960–2007. Analysis of the balance was used to evaluate the changes in the hydrological regime. The dynamic of water exchange via the Strait is very much important and depends on: the change of water level between the Baltic Sea and the Curonian Lagoon, the hydrological regime of the rivers and the changes in the permeability of the Strait as a result of dredging projects.

Keywords *Curonian Lagoon,* Baltic Sea, *water balance, climate change, hydrological regime, river runoff.*

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INTRODUCTION

Lagoons are widespread all over the world: in North America they constitute 17.6% of the total length of the shores, in South America – 12.2%, in Europe – 5.3%, in Africa – 17.9%, in Asia – 13.8% and in Australia – 11.4% (Barnes 1980). Lagoons are rather different since their area may reach even up to 10.200 km^2 (e.g. the Pata Lagoon in Brazil). The average water depth is about 1–3 m, and it is always less than 5 m, but this is not applied to straits that connect the lagoons with the sea. The latter is dredged in order to adjust it to shipping. Lagoon is an invaluable component of the nature and ecosystem of the shores and it also gives comfortable possibilities for the surrounding inhabitants to develop fishery and tourism. They are the most productive of all the coastal components (Gonenc, Wolflin 2005). The balanced function of the lagoons might assure their sustainable use in the future. Therefore, during the interference into their natural hydrological regime, it is necessary to ensure a minimal impact on environment or no impact at all.

Lagoons both in Europe and in the rest world are investigated from the hydrological and hydrodynamic point of view. M. L. Spaulding reviewed models of the circulation and mixing dynamics of lagoon systems, proceeding from simple correlation analyses to full-scale numerical hydrodynamic and pollutant transport models. Application of simplified models is provided to illustrate the impact of various management strategies on selected lagoon systems (Spaulding 1994). B. Kjerfve and K. E. Magill studied shallow coastal lagoon hydrodynamics, water exchange with the ocean, sedimentary processes associated with river hydrological cycles and wind condition (Kjerfve, Magill 1989). N. H. More and D. J. Slinn have analyzed Caimanero–Huizache lagoon system on the Pacific coast in Mexico during 1977–1978. The investigations of river inflow, precipitation, evaporation and outflow into the ocean were carried out, and briefly compared with other lagoon systems of the Pacific coast in Mexico (More, Slinn 1984).

Lately, the analysis of hydrological changes of lagoons, regarding climate change, has been begun. As

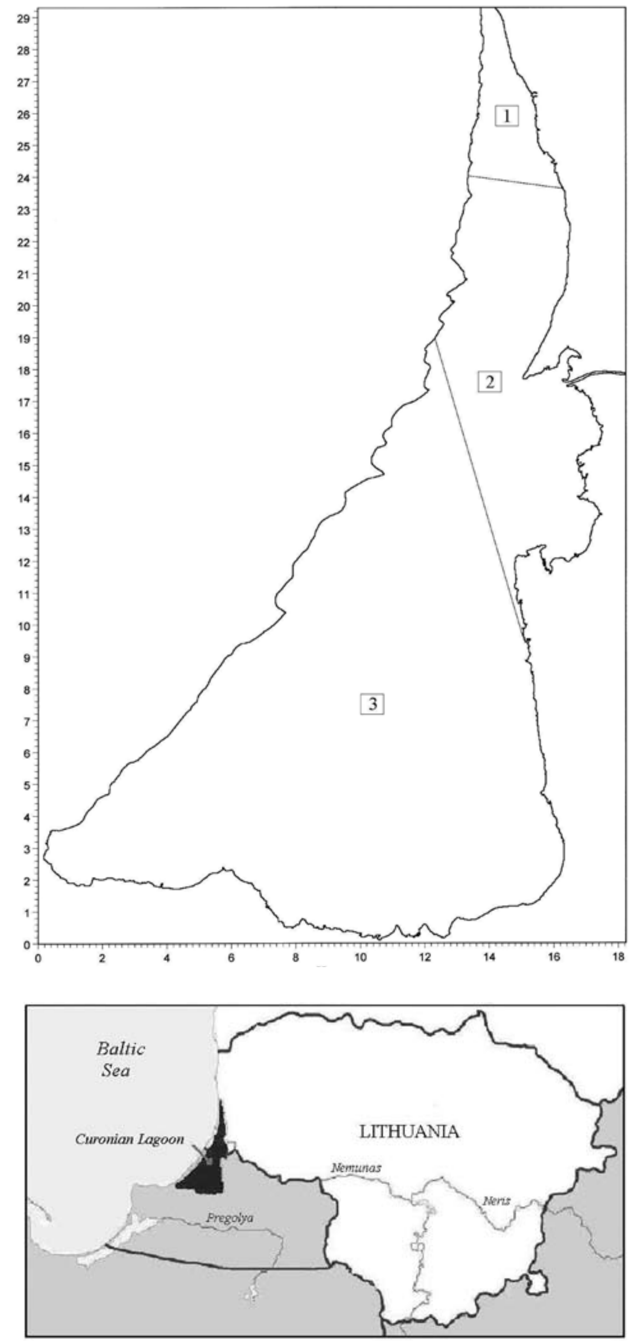

Fig. 1. Division of the Curonian Lagoon to separate ranges applying Tysen range method. Polygons: 1 - Klaipėda MS; 2 - Ventė MS; 3 - Nida MS. Inset: locality of the Curonian Lagoon, eastern coast of the Baltic Sea.

concerns the Curonian Lagoon, the impact of climatic and anthropogenic factors on hydrodynamic regime was analyzed by G. Stankūnavičius and R. Žaromskis (2005).

STUDY AREA

The Curonian Lagoon is the only and biggest fresh water basin in Lithuania (Fig. 1). Its greater part belongs to Russia (1171 km^2), whereas 413 km^2 is in the territory of Lithuania (Dubra 1978). The Curonian Lagoon distinguishes in its area, landscape and uniqueness of fauna. During the development of Klaipėda State Seaport, the northern part of the Curonian Lagoon, connecting the lagoon with the Baltic Sea via the strait, has been dredged; the quays have been reconstructed and newly built. Due to these reasons, the permeability of the strait has been changed and this has influenced the changes in the structure of flows (Gailiušis, Kriaučiūnienė 1999), sediment transport (new erosion and accumulation places) (Kriaučiūnienė, Gailiušis 2004), and hydrological regime of the northern part of the lagoon (Gailiušis 2005).

E. Červinskas has calculated the water balance of the Curonian Lagoon for the first time (Červinskas 1956). J. Dubra has continued the calculations of water balance (Dubra, Červinskas 1968), submitting the research material about the fluctuations of water level and the flow regime (Dubra 1978). The water balance for long period of 1955–1988 has been analyzed by B. Gailiušis, M. Kovalenkovienė and A. Jurgelėnaitė (Gailiušis *et al.* 1992). All the components of the water balance have been calculated using direct measurement data, which added accuracy to the work. Subsequently, the calculations have been extended up to 1995 (Gailiušis *et al.* 2001).

During a long–term period, the water balance components of the Curonian Lagoon have been changed. The changes were caused by the following natural processes: 1) cyclic watery changes of precipitation and river inflow (climate warming has already changed the annual distribution of inflow) (Kriaučiūnienė *et al.* 2008); 2) evaporation and its changes; and 3) water exchange via the Strait (due to water level difference between the Baltic Sea and the Curonian Lagoon). Additionally, the changes of river inflow to the Curonian Lagoon may be caused by the anthropogenic activities: 1) installation of ponds in the basin of Nemunas River (Kriaučiūnienė, Gailiušis 1998); and 2) shift of water exchange via the strait, caused by the dredging of Klaipėda Strait and the reconstruction of the harbor entrance (Gailiušis 2005; Jurgelėnaitė, Šarauskienė 2007).

Currently there is a great deal of discussions on the limit where the impact of natural processes ends and the anthropogenic impact begin. Therefore, a necessity to renew the quotas of the Curonian Lagoon water balance emerges. The last calculation of water balance, covering the period of 1958–1995, was done based on the hydro–meteorological information from the southern part of the Curonian Lagoon, belonging to Russia. Since presently these data are not accessible, it is necessary to recalculate the water balance. Moreover, it seems essential to apply the methodology of calculations that would provide enough data from the hydro–meteorological stations, located on the territory of Lithuania, and the calculation accuracy would not become worse.

The goal of this article is to estimate the water balance of the Curonian Lagoon for the period of 1960–2007, regarding climate change and anthropogenic factors.

METHODS AND MATERIAL

Water balance

The water balance of any water basin is characterized by an equation:

Income – Losses = Change in the volume (1)

Water balance can be assessed as a method allowing determination of water exchange processes in the Lagoon and its level of hydro-meteorological investigation. The most important fact is that water balance method enables calculating this element of water balance, which can be hardly measured directly. Such elements could be underground outflow or outflow of melting ice, but it is not applied for determination of filtration as the error becomes significant and the calculation loses the sense (Nezichovski 1975).

The water balance of the Curonian Lagoon (further referred as Lagoon) has been calculated applying the following equation (Gailiušis *et al.* 1992):

$$(Q_U + P - Z) + (Q_J - Q_M) = \pm \Delta V \qquad (2)$$

Where: Q_U – river inflow to the Curonian Lagoon;
P – precipitation on the surface of the Curonian Lagoon;
Z – evaporation from the Curonian Lagoon;
Q_J – inflow from the Baltic Sea to the Curonian Lagoon;
Q_M – outflow from the Curonian Lagoon to the Baltic Sea;
ΔV – change in the volume of the Curonian Lagoon.

Similarly to the previous studies of water balance (Červinskas 1956; Dubra, Červinskas 1968; Dubra 1978; Gailiušis *et al.* 1992; Gailiušis *et al.* 2001), the inflow of groundwater and the river ice, brought to the lagoon during ice–drift and outflowing into the sea, were not assessed.

River inflow

Daily river discharge data of the Nemunas at Smalininkai, the Šešupė at Kudirkos Naumiestis, the Šešupė at Dolgoje, the Šešupė at Marijampole, the Jūra at Tauragė, the Šešuvis at Skirgailiai, the Minija at Kartena, the Akmena–Danė at Kretinga, the Akmena–Danė at Tūbausiai and the Deimena at Gvardeisk (up to 1988) were used for calculations of river inflow into the lagoon (Hydrometeorological... 1960–1989; Lithuanian... 1990–2007).

River inflow calculation methodology was developed using direct data of water measurement stations (further – MS) and methods of analogy for the determination of runoff from those parts of the basin where the runoff was not measured. The water discharge from the stations, where the measurements were executed, was recalculated for the estuaries of the rivers (by multiplying to the coefficients, received according to the ratio of the areas of the basins) evaluating the time of flowing. The areas of river basins and required unit runoff were taken from the edition on the hydrography and runoff of the Lithuanian rivers (Gailiušis *et al.* 2001).

The inflow was calculated using this method in order to evaluate different hydrological regime (the runoff distribution per year) of the Nemunas basin, including Šešupė (87.1% of the area of the lagoon basin), and the rivers of western Lithuania and the Kaliningrad region (12.9% of the area of the lagoon basin). Flash–flood regime is peculiar for the rivers of western Lithuania and it has a great impact on the fluctuations of water level in the Curonian Lagoon.

Precipitation

Precipitation in the territory of Lithuania was measured for the period of 1960–2007 in the MS of Klaipėda, Nida and Ventė; the precipitation was calculated for a period of one month. Calculating the input of separate MS into the total quantity of precipitation, the method of Tysen experimental range was applied (Martin, McOutcheon 1999). It was determined that Klaipėda MS represents 4.3% of the total surface area of the lagoon, Ventė MS – 20.4% and Nida MS – 75.3%. Using the sums of precipitation and weight coefficients in different MS, the quantity of precipitation that had fallen on the surface of the lagoon during separate months was calculated.

Evaporation

No data are available on evaporation from the surface of the water of the lagoon; therefore, it was calculated according to the empirical formula, based on hydro–meteorological elements (Poška, Punys 1996).

The quantity of evaporation for separate months was calculated; their sum shows the annual evaporation from the surface of the lagoon in mm. All parameters of evaporation equation were determined according to the data of Nida MS. The dates of freezing of the lagoon were calculated as an arithmetic average between the covering of the lagoon with ice at Nida and Juodkrantė. The calculations were made for the period of one month.

Change in volume

In order to calculate the change in the water volume, it is necessary to know the daily average water level of the lagoon and river inflow. The sum inflow to the lagoon was calculated applying the above discussed methodology. Juodkrantė hydrological station was chosen for the evaluation of the fluctuation of the water level of the lagoon. Its water level properly reflects the fluctuations of water level of the whole lagoon. This can be grounded by the relation scheme between water level of the lagoon at Juodkrantė and average water level, calculated using the data of Klaipėda, Juodkrantė, Nida, Ventė and Otkrytoje stations (Fig. 2).

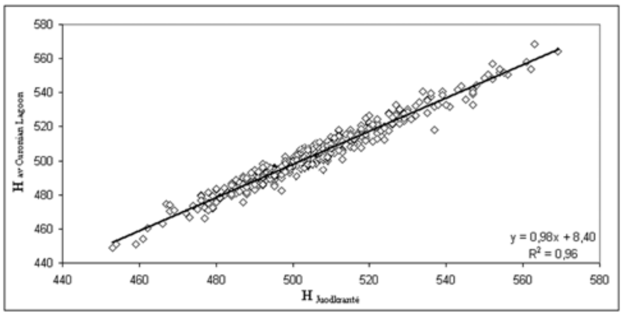

Fig. 2. Relation between water level at Juodkrantė and average water level in the Curonian Lagoon.

For the purpose of developing this relation scheme, the average monthly water levels of 1955–1985 at Klaipėda, Juodkrantė, Nida, Ventė and Otkrytoje were used. The average water level of the lagoon was calculated according to the data of five stations (Gailiu šis *et al.* 1992). The average water level of the lagoon may also be calculated applying the above mentioned methodology. When Lithuania became an independent state, there was no possibility to use all the hydro–meteorological information from the southern part of the lagoon; therefore, alternative solutions were necessary.

Knowing the average water level of the lagoon, the change in the volume between the adjacent days for the whole period under investigation can be calculated. According to the dependence of the surface water area on the water level (Červinskas 1955), and using data of water level at Juodkrantė the surface area of the lagoon has been calculated day by day. Using daily data of the water level (ΔH) and the water surface area changes, the change in the volume of the lagoon expressed in discharge (m^3/s) could be calculated.

Water exchange discharges between the sea and the lagoon were calculated according to the daily change in the volume and the sum river inflow. This has been done by subtracting the sum of river inflow from the change in the volume. If the discharge is negative, it shows that the water flows from the Curonian Lagoon into the Baltic Sea, and if it is positive, the water flows from the Baltic Sea to the Curonian Lagoon.

Analysis of water balance components

Different mathematical statistics methods have been applied for the evaluation of water balance components and their change. Non–parametric Mann–Kendall test of statistic analysis is recommended by the World Meteorological Organization and it was applied for the determination of change trends in meteorological or hydrological characteristics (Maidment 1993). Using this method, positive or negative trends of characteristics under investigation were determined with 30% reliability level and significant positive or negative trends with 5% reliability level.

Modulus coefficient K is a relation of the each observation data with average of investigated time series (Gailiušis *et al.* 2001). The synchronic changes and periodic river runoff fluctuations are illustrated by the average modulus coefficient $\overline{K}$.

The accuracy of the average calculation of long–term water balance depends on the accuracy of calculation of each member. The sum balance error was calculated as the sum of standard errors of all balance elements (Čekanavičius, Murauskas 2000):

$$\delta = \pm\sqrt{\delta_1^2 + \delta_2^2 + \ldots + \delta_6^2} \quad (3)$$

Where: δ – calculation error sum of water balance components of the Curonian Lagoon; $\delta_1, \delta_2, \ldots, \delta_6$ – river inflows to the Curonian Lagoon, precipitation on the surface water of the Curonian Lagoon, evaporation from the Curonian Lagoon, inflow from the Baltic Sea to the Curonian Lagoon, outflow from the Curonian Lagoon to the Baltic Sea and errors of changes in the volume of the Curonian Lagoon.

If the received balance credibility is even or lower than sum error **δ**, then the calculated water balance is rather accurate.

RESULTS AND DISCUSSION

River inflow

River inflow comprises a greater part of the income of water balance; therefore, it is important to evaluate it accurately. River inflow of the period of 1960–2007 was calculated with the daily interval using the data of direct measurements and applying the methods of analogy. The average of yearly river inflow of the above mentioned period was 21 847 km^3, fluctuated from 13 967 km^3 (1969) to 30 041 km^3 (1980) (Fig. 3a). Cyclic change of the abundance of water is peculiar for Lithuanian rivers (Meilutytė-Barauskienė *et al.* 2008). Modulus coefficient $\overline{K}$ is 0.93, comparing the runoff data of the Nemunas at Smalininkai for the period of 1960–2007 with long–term series data from 1812 to 2007. The period under investigation covers two dry ($\overline{K}$ = 0.84 in 1963–1977 and $\overline{K}$ = 0.90 in 1991–2006) and one watery ($\overline{K}$ = 1.06 in 1978–1990) phases of the cycle. Applying Mann–Kendall test, it was determined that during the period till 1982 the trend of river inflow to the lagoon was positively significant (reliability of 95%), and from 1983 the inflow decreased, but the decrease was not statistically significant.

Many scientists worked on the climate change and its impact on the river runoff (Reihan *et al.* 2007; Beldring *et al.* 2008; Kriaučiūnienė *et al.* 2008). As the runoff slightly decreases, the changes in the distribution of runoff may be observed in a year's time. The analysis of annual distribution of runoff has been performed by dividing the period into four parts, 12 years in each (1960–1971, 1972–1983, 1984–1995, 1996–2007). The part of annual runoff (%), comprising the seasonal runoff during separate periods was calculated (Fig. 3b).

The summer runoff has slightly changed, from 15.6% to 16.9%, whereas autumn runoff fluctuated between 18.5% and 22.5%. The greatest changes took place in the distribution of winter and spring runoff. Significant change of runoff took place between 1960–1971 and 1972–1983: in winter the runoff increased by almost 5%, and in spring decreased by 9%. Comparing the results in the beginning and in the end of the period under investigation, the following essential re–distribution of runoff was determined: in the period of 1960–1971 the difference between spring and winter runoff reached 24.4% (in winter 20.7%, in spring 45.1%), and in the period of 1996–2007 only 6.4% (in winter 28.9%, and in spring 35.3%). Such change of long–term river runoff to the Curonian Lagoon proved that spring floods and maximal discharges are being stabilized earlier and their values have decreased. In order to verify this fact, the hydrographs were made, showing the average long–term sum river inflow to the lagoon in the beginning (1960–1971) and in the end (1996–2007) of the period (Fig. 3c). The supposition proved correct, as comparing the river inflow in the beginning and in the end of the period under investigation, significant early spring flood coming was observed (Fig.4a). The trends of analysed dates and quantities of Q_{max} show that maximum river discharges have been steadily appearing at earlier date (Fig. 4a), whereas the values of Q_{max} have decreased (Fig. 4b).

Applying Mann–Kendall test for Q_{max} date, it was determined that the trend is negatively significant (reliability of 90%), i.e. Q_{max} date appears earlier. Additionally, the trend was negatively significant, analyzing Q_{max} in the period of 1960–2007. Such runoff changes can be explained by the increasing temperature of cold period, decrease of a number of days with snow cover and snow cover becoming thinner (Bukantis *et al.* 2001). Since the cold period is becoming warmer, a greater amount of precipitation falls in a form of rain and quicker comes to the rivers, forming the earlier flood runoff; in this way the difference between winter and spring runoff has decreased. Therefore, the hydrograph becomes steadier and Q_{max} decreases. Scientists of Nordic countries have made similar results as they determined that the reliability of great floods decreased, which is related to the decreasing spring runoff (Hisdal *et al.* 2004).

Precipitation and evaporation

Calculating these two water balance elements, the area of the lagoon is to be evaluated as a variable parameter, depending on the average water level of the lagoon. Under the case of investigation, the water level at Juodkrantė has reflected average level of the Lagoon. Analysing water level data at Juodkrantė, it was determined that water level rise in the period of 1960–2007. The same conclusions were drawn by other scientists: the water level in the lagoon had been raising on the average 0.3 cm a year, and it was on the rise by 8 cm comparing the periods of 1960–1975 and

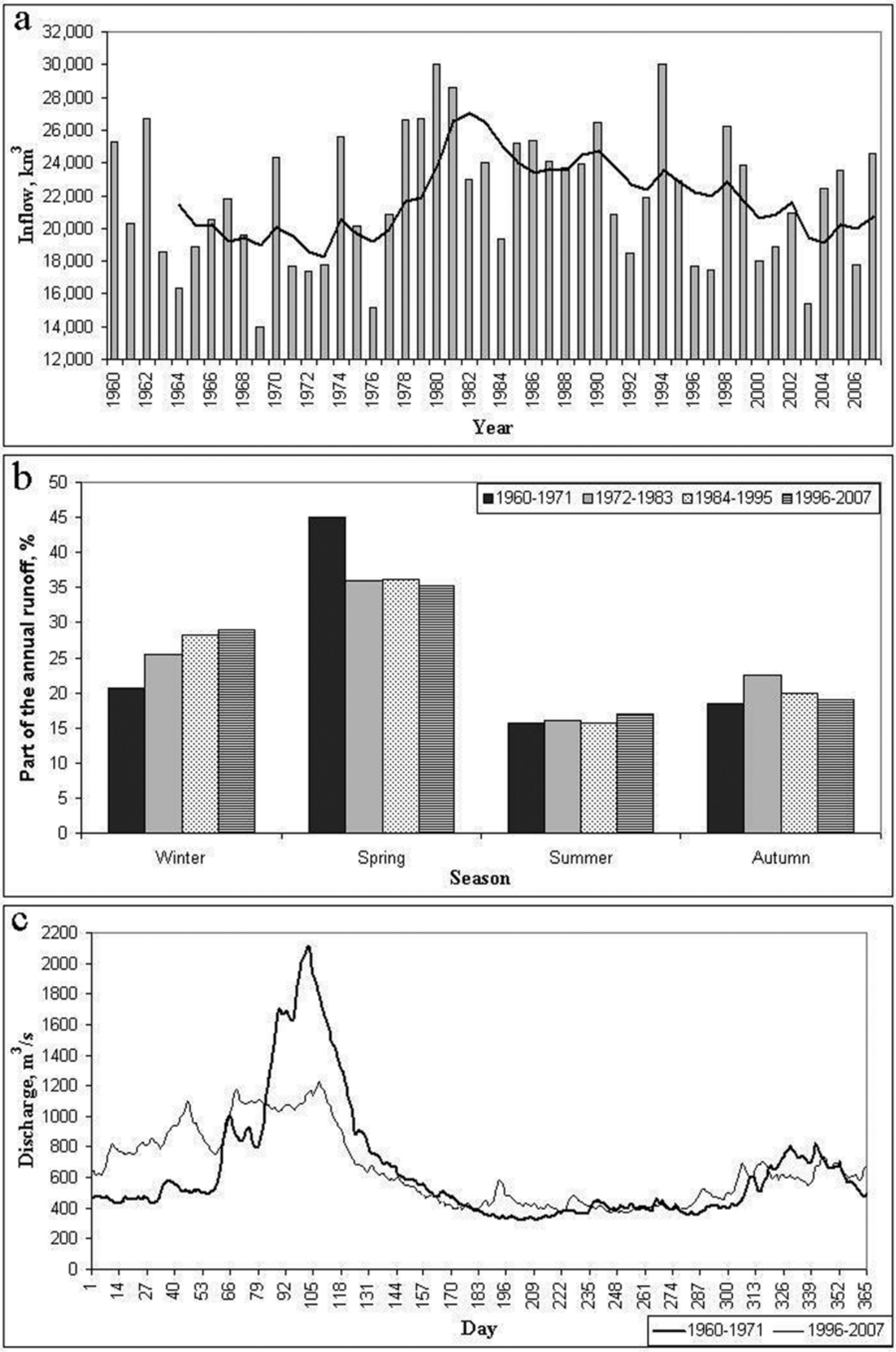

Fig. 3. River inflow to the Curonian Lagoon in the period of 1960–2007: a–river inflow; b–distribution of seasonal runoff; c–average sum river inflow in the period of 1960–1971 and 1996–2007.

1991–2005 (Dailidienė *et al.* 2005; Dailidienė *et al.* 2006; Dailidienė 2007). The surface area of the lagoon increased as its water level had risen. Therefore, the quantity of precipitation falling on the surface of the lagoon and evaporation should also increase.

Moreover, precipitation was changing unevenly in the period of 1960–2007: its quantity slightly increased (Fig. 5a), which is shown by a significant positive trend (reliability of 90%). Analysing the distribution of long–term precipitation among the seasons (Fig. 5b), it was determined that the quantity of winter season precipitation increased only by 2.5% comparing the periods of 1960–1971 and 1996–2007, and it decreased by 3.2% in spring season. In summer, the quantity of precipitation slightly changed (by 1.4% comparing the periods of 1960–1971 and 1996–2007), while in autumn, the quantity of precipitation increased by 2.3%.

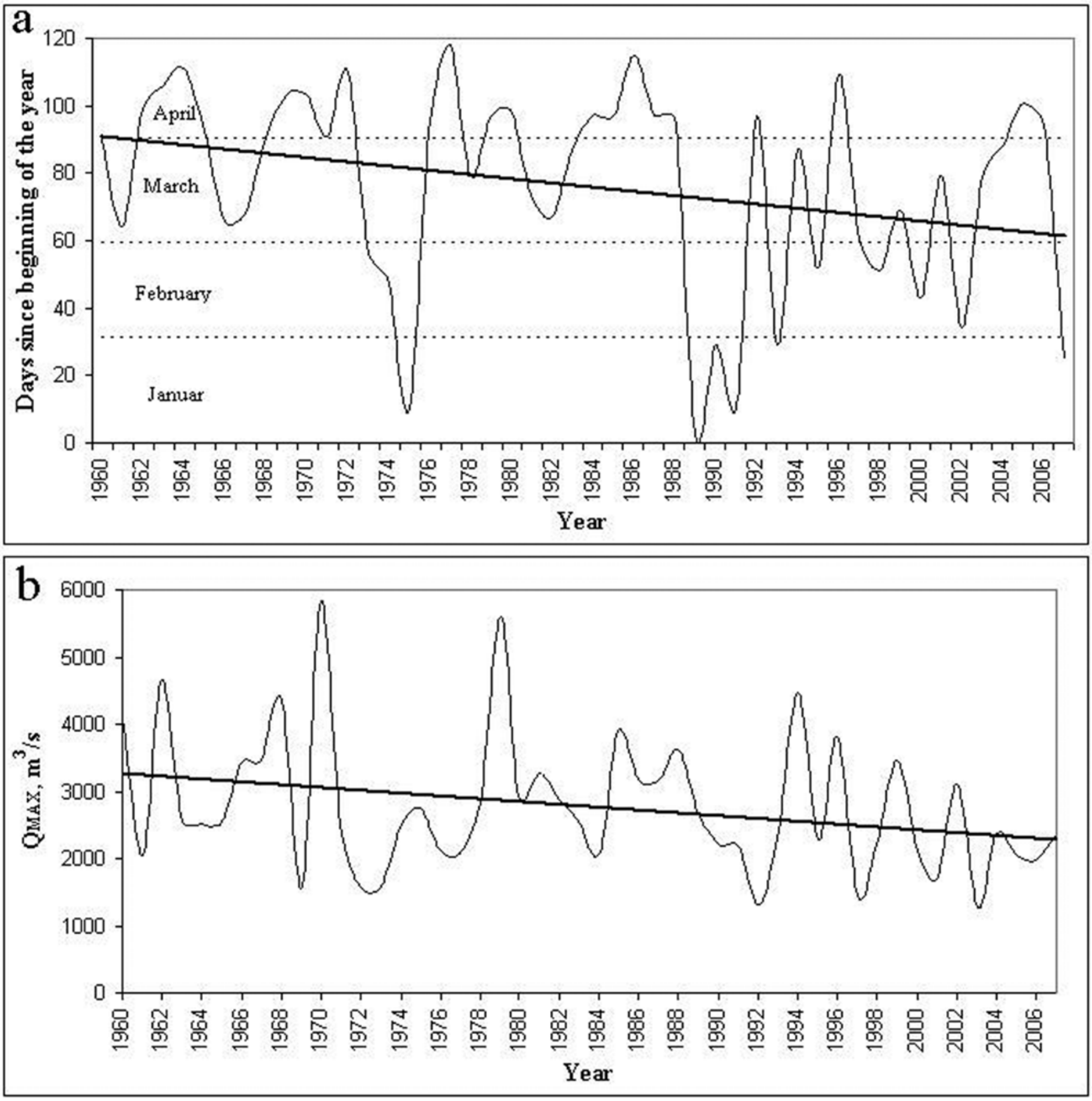

Fig. 4. Maximal sum river runoff to the Curonian Lagoon in the period of 1960–2007: a–dates; b–maximal discharge.

Evaporation of 1960–2007 was also described (Fig. 6a): the average annual evaporation was 1.006 km^3, and it fluctuated from 0.815 km^3 (in 1996) to 1.293 km^3 (in 1983). In summer average evaporation was 0.492 km^3 (49% of annual quantity), in autumn – 0.240 km^3 (23.9% of annual quantity), in spring – 0.199 km^3 (19.8% of annual quantity) and in winter – only 0.074 km^3 (7.4% of annual quantity). Analysing seasonal evaporation (expressed as part of the annual evaporation, %), it was observed that there were no significant differences in separate periods (1960–1971, 1972–

1983, 1984–1995, 1996–2007) (Fig. 6b). Comparing the periods of 1960–1971 and 1996–2007, the least changes of evaporation were noticed in winter (only by 0.3%) and in autumn (by 1.1%); slightly greater changes were in spring (increasing by 3.2%) and in summer (decreasing by 2.3%).

Evaporation is closely linked to wind velocities, which decreased only from 1983 but increased till 1982 (Fig. 6a). Analysing wind velocity data from Nida MS, it was observed that in the period of 1960–1982 the trend of wind velocity was positively significant (reliability of 99%), and since 1983 the trend has been negatively significant (reliability of 99.9%) and the investigations made by I. Dailidienė prove these conclusions. According to Dailidienė (2007), in the period of 1961–2005, wind velocity decreased in Nida and Klaipėda. The comparison of wind velocities of Nida MS and fluctuations of evaporation from the Curonian Lagoon showed that they have changed rather synchronically (Fig. 6a).

Correlation relationship between wind velocity and evaporation reached 0.64 during all the period under investigation, and in the period of 1983–2007 it was 0.75. The calculated coefficient of correlation is significant, taking into consideration the fact that the evaporation also depends on the temperature of water and the air, water vapour pressure, humidity deficit, duration of coverage of the Lagoon with ice and wind direction.

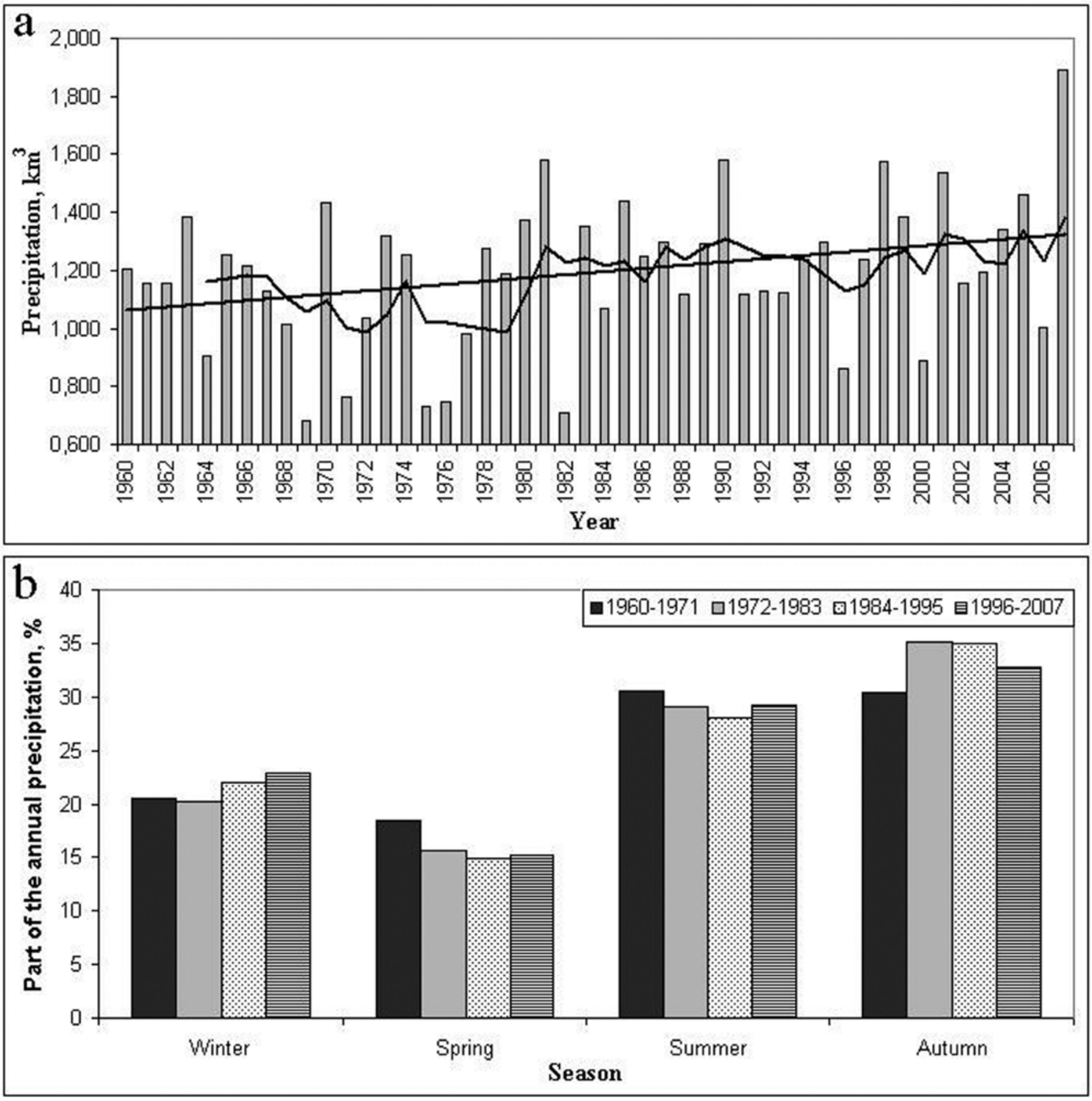

Fig. 5. Precipitation on the Curonian Lagoon in the period of 1960–2007: a–precipitation; b– distribution of seasonal quantity of precipitation.

Change in volume

Calculating the change in volume, water exchange via the Klaipėda Strait has been analysed. It was determined that the average long–term runoff from the Curonian Lagoon to the Baltic Sea (Q_M) was 27 655 km^3 during the investigated period of 1960–2007 (Fig. 7a). The average long–term inflow from the Baltic Sea to the Curonian Lagoon (Q_J) reached 6125 km^3 (Fig. 7b). The dredging of Klaipėda Strait changed its permeability. It is important to know how Q_M and Q_J changed during the period under investigation because these changes are related to the dredging of the strait and natural changes, i.e. climate change.

In the period of 1960–2007, the runoff trend of Q_M was positively significant (Fig. 7a). Applying the moving five–year average method, the period was divided into two parts: before 1982 and after 1983. During the former period of time, the trend of the runoff from the lagoon to the sea was positively significant (reliability of 95%), while the latter showed a slight decrease (statistically insignificant).

Long–term runoff from the lagoon to the sea fluctuates synchronically with the long–term river inflow (Fig. 8). Thus, the analysis of the long–term inflow from the Baltic Sea to the Curonian Lagoon (Q_J) showed that the inflow increased (Fig. 7b). Following the moving five–year averages, the whole period may be divided into two parts: before 1982 and after 1983. During the first period the inflow from the sea to the lagoon decreased, but increased during the second one.

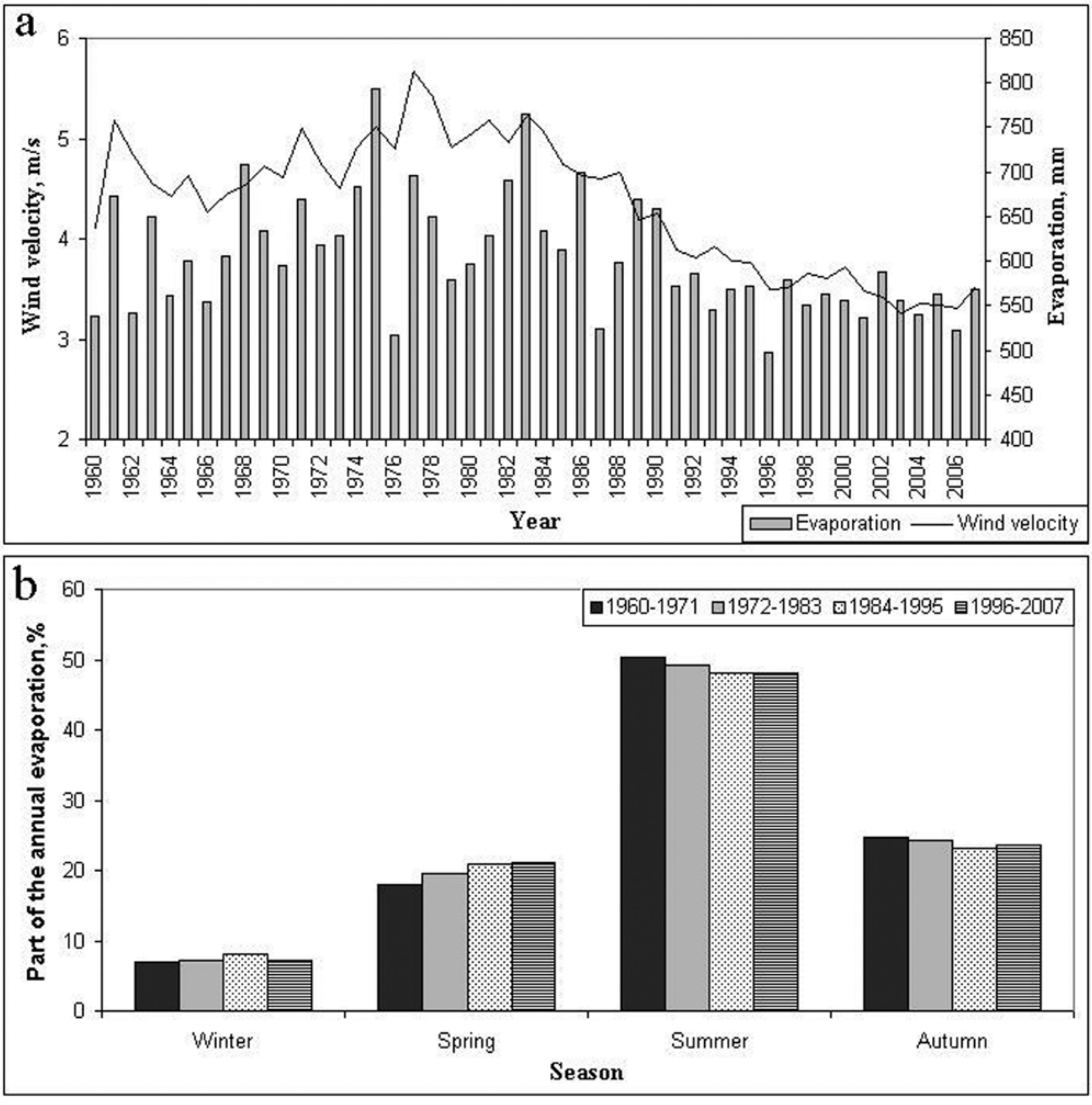

Fig. 6. Change of evaporation in the period of 1960–2007: a– evaporation and wind velocity (Nida MS); b–distribution of seasonal part of the annual evaporation (%).

In 1960–2007 the trend of Q_J was positively significant (reliability of 99.9%), while in the period before 1982 a slight decrease is observed (statistically insignificant), and after 1983 the trend has been positively significant (reliability of 90%).

Water balance of the Curonian Lagoon is given in Table 1. The sum calculation error of different water balance elements according to the formula 3 was evaluated. The results show that sum river inflow error to the Curonian Lagoon is 0.581 km^3, precipitation – 0.037 km^3, evaporation – 0.017 km^3, inflow from the Baltic Sea – 0.182 km^3, runoff to the Baltic Sea – 0.572 km^3 and change in the volume of the Curonian Lagoon – 0.096 km^3. The sum error of water balance components is 0.842 km^3. As calculated error of water balance is 0.468 km^3, and the allowed error is 0.842 km^3, it could be stated that the water balance was calculated rather accurately. The changes of Q_M and Q_J can be analysed in two periods of the same length (1963–1982 and 1983–2002) (Fig. 9). The river inflow of these periods (km^3) is 21.169 (1963–1982) and 22.468 (1983–2002), i.e. they differ only by 5.8%.

The inflow from the sea to the lagoon during the period of 1963–1982 was by 20.6% lower than during the period of 1983–2002. Such change in inflow could not predetermine by the river inflow changes and the port dredging works (Jurgelėnaitė, Šarauskienė 2007). An important factor, predetermining the direction of inflow, is the difference of water levels between the Baltic Sea and the Curonian Lagoon. The change of the Baltic Sea level is natural and the changed river inflow, caused by anthropogenic activities, influences

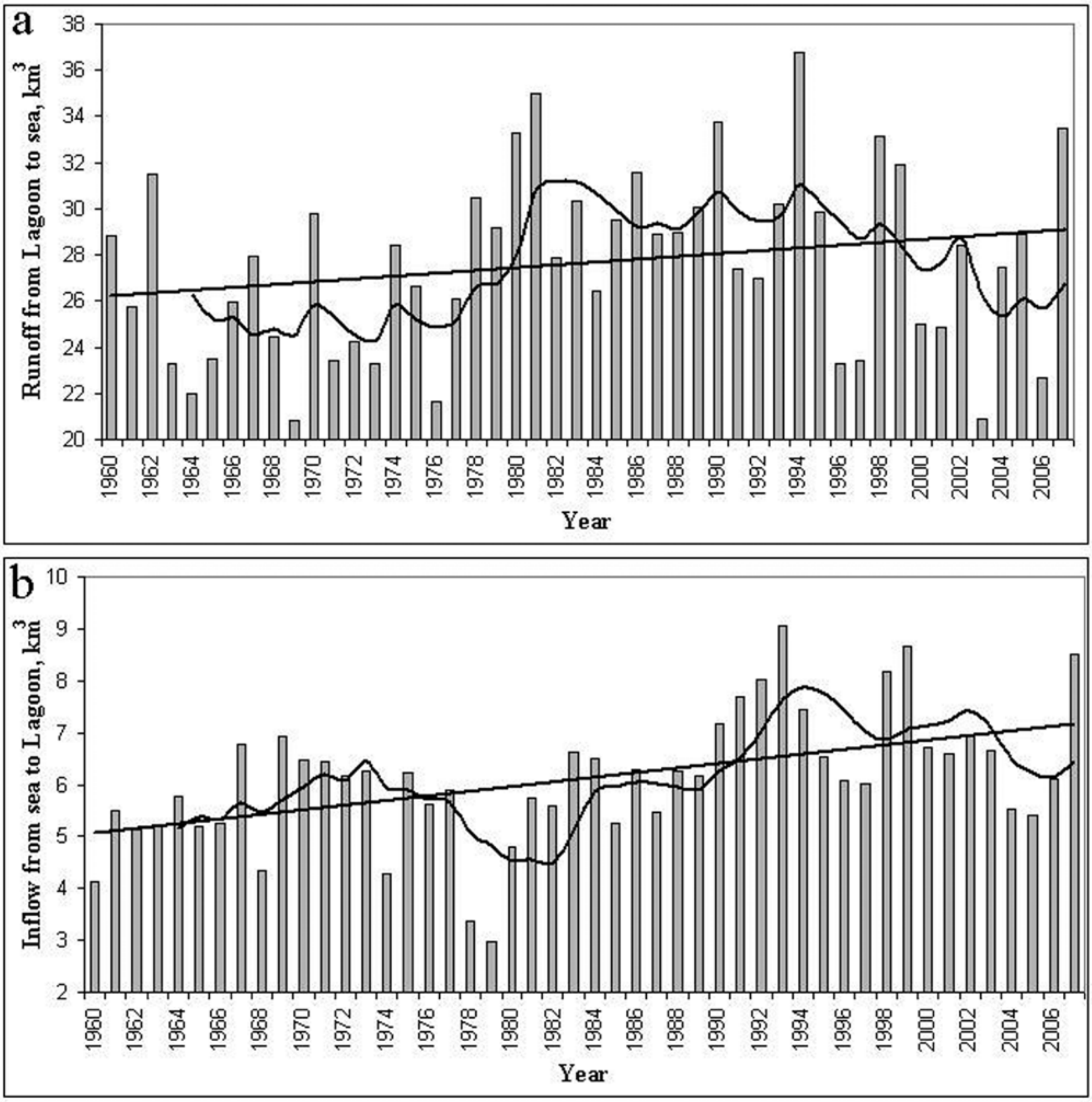

Fig. 7. Water exchange through the Klaipėda Strait: a–runoff from the Curonian Lagoon to the Baltic Sea (Q_M); b–inflow from the Baltic Sea to the Curonian Lagoon (Q_J).

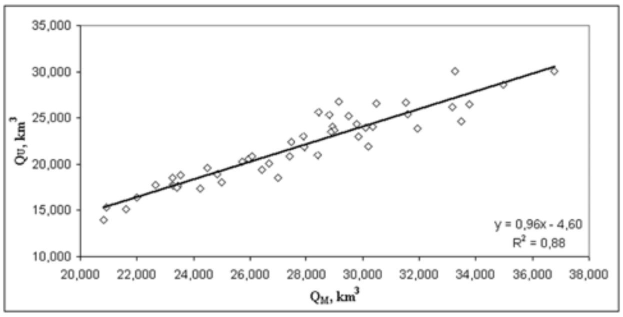

Fig. 8. Relation between the runoff from the Curonian Lagoon to the Baltic Sea (Q_M) and sum river inflow to the Curonian Lagoon (Q_U).

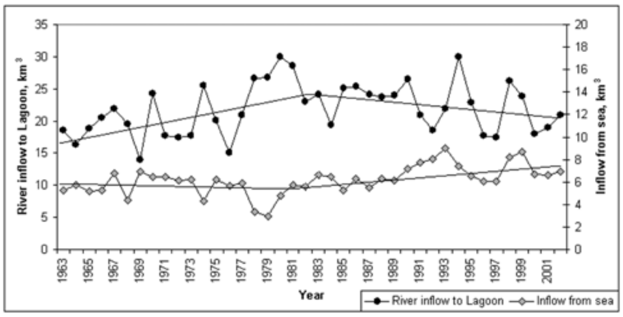

Fig. 9. Change of inflow from the Baltic Sea to the Curonian Lagoon and river inflow to the Lagoon in 1963–2002.

Table 1. Water balance of the Curonian Lagoon during the period of 1960–2007 (km^3).

Balance components	Month												Annual
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
River inflow, (Q_U)	1.949	1.760	2.804	3.629	1.868	1.230	1.140	1.139	1.134	1.419	1.826	1.948	21.847
Inflow from sea to lagoon, (Q_J)	0.482	0.327	0.290	0.244	0.324	0.476	0.509	0.537	0.658	0.747	0.885	0.647	6.125
Precipitation, (P)	0.087	0.062	0.064	0.060	0.067	0.094	0.120	0.135	0.131	0.136	0.131	0.107	1.194
Income	2.518	2.149	3.157	3.932	2.259	1.800	1.768	1.811	1.923	2.302	2.842	2.703	29.166
Runoff from lagoon to sea, (Q_M)	2.450	2.262	2.968	3.969	2.324	1.537	1.537	1.667	1.748	2.129	2.524	2.540	27.655
Evaporation, (Z)	0.023	0.020	0.030	0.055	0.115	0.155	0.174	0.163	0.120	0.073	0.047	0.032	1.006
Losses	2.473	2.281	2.998	4.024	2.439	1.692	1.711	1.829	1.868	2.202	2.572	2.572	28.661
Change in the volume	0.001	-0.010	-0.050	0.031	0.078	0.023	-0.033	-0.015	-0.023	0.025	-0.046	0.056	0.037
Error	0.044	-0.123	0.210	-0.123	-0.257	0.086	0.090	-0.004	0.078	0.075	0.317	0.075	0.468

the water level of the Curonian Lagoon (Kriaučiūnienė, Gailiušis 1998). In the case of a great river inflow into the lagoon, the water level in it rises and the water flows via the strait into the Baltic Sea and vice versa, whereas considering small river inflow into the lagoon, the water level of the lagoon starts to lower and water flows from the sea to the lagoon (inverse dependence) (Fig. 10).

Water quantity flowing via the Klaipėda Strait to the Curonian Lagoon also depends on the strength and direction of wind from the point of view of the harbour entrance. It is determined that the inflow, bigger than 1000 m^3/s, from the Baltic Sea to the Curonian Lagoon was by 75% in those cases when NW, W and SW winds were blowing stronger than 5 m/s.

The conclusion could be drawn that the changes of inflow from the Baltic Sea to the Curonian Lagoon were predetermined by natural–anthropogenic factors: natural fluctuation of the Baltic Sea water level, the changed hydrological regime of river inflow due to the climate change and anthropogenic activities, increased permeability of the Klaipėda Strait.

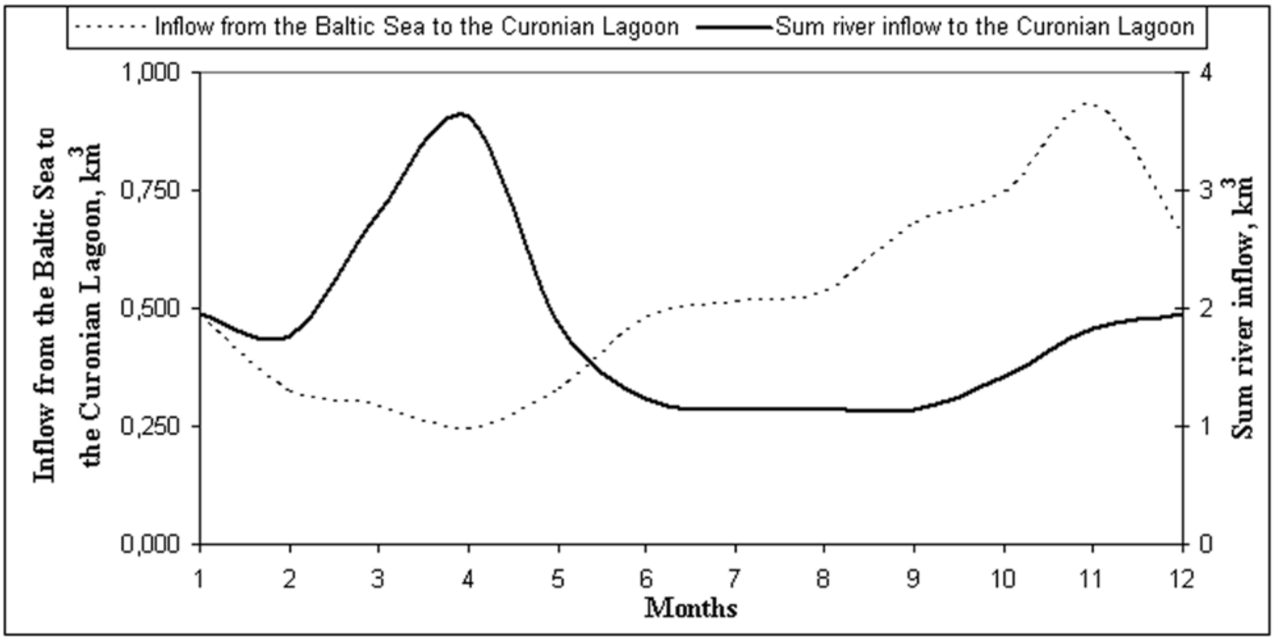

Fig. 10. Distribution of inflow from the Baltic Sea to the Curonian Lagoon and sum river inflow to the Curonian Lagoon per year during the period of 1960–2007.

CONCLUSIONS

The results of long–term water balance calculation in the Curonian Lagoon show that sum river inflow is 21.847 km^3/year, precipitation – 1.194 km^3/year, and evaporation 1.006 km^3/year. Long–term salt and fresh water exchange via the Klaipėda Strait is the following: inflow of salt water from the Baltic Sea to the Curonian Lagoon – 6.125 km^3/year and fresh water runoff from the Curonian Lagoon to the Baltic Sea – 27.655 km^3/year.

Redistribution of sum river runoff to the Curonian Lagoon during a year was observed. A part of runoff moved from spring to winter, Q_{max} dates came earlier and Q_{max} quantities decreased; therefore, the runoff distributed among the seasons more evenly.

During the period of investigation, the inflow from the Baltic Sea to the Curonian Lagoon increased. It was determined that in the period of 1960–2007, the inflow trend from the Baltic Sea to the Curonian Lagoon was positively significant (reliability of 99.9%). In the period before 1982 a slight decrease was observed (statistically insignificant), and since 1983 the trend has been positively significant (reliability of 90%).

During the period of 1960–2007, the quantity of precipitation changed a little, the average long–term value reached 1194 km^3. However, evaporation decreased and the average long–term value was only 1006 km^3. Decrease of evaporation can be explained by the decrease of wind velocity at Nida MS since the trend of wind velocity measured at Nida MS in the period of 1960–2007 was negatively significant (reliability of 99.9%).

Great seasonal changes of the river inflow into the Curonian Lagoon were caused by the increase of temperature during the cold period and due to this, a greater part of precipitation fell in the form of a rain and reached the rivers quicker, forming earlier floods and in this way decreasing the difference between winter and spring runoffs. These changes appeared as a consequence of climate change, but the increase of inflow from the Baltic Sea to the Curonian Lagoon can be linked to natural–anthropogenic factors.

Acknowledgments

This study was funded by Nordic Energy Research within the research project “Climate and Energy Systems”. Center of Marine Research (Klaipėda) and Lithuanian Hydrometeorological Service (Vilnius) permitted to use hydrometeorological data which is appreciated very much. Author is grateful to the reviewers for helpful comments that allowed to improve the quality of manuscript.

References

Barnes, R. S. K. 1980. *Coastal Lagoons.* Cambridge University Press, Cambridge, UK, 106 pp.

Beldring, S., Engen-Skaugen, T., Forland, E. J. 2008. Climate change impacts on hydrological processes in Norway based on two methods for transferring regional climate model results to meteorological station sites. *Tellus 60A*, 439–450.

Bukantis, A., Gulbinas, Z., Kazakevičius, S., Kilkus, K., Mikelinskienė, A., Morkūnaitė, R., Rimkus, E., Samuila, M., Stankūnavičius, G., Valiukevičius, G., Žaromskis, R. 2001. *The influence of climatic variations on physical geographical processes in Lithuania*. Vilnius, 280 pp. [Klimato svyravimų poveikis fiziniams geografiniams procesams Lietuvoje; in Lithuanian].

Čekanavičius, V., Murauskas, G. 2000. *Statistics and its applications. Book I.* TEV, 240 pp. [Statistika ir jos taikymas; in Lithuanian].

Červinskas, E. 1955. Bathygraphic curve of the Curonian Lagoon. *Scientific Reports, Institute of Geology and Geography, Volume 1*, 107–114. [Kuršių marių batigrafinė kreivė; in Lithuanian].

Červinskas, E. 1956. Issue of average annual water balance of Curonian Lagoon. *Works of the Academy of Sciences, B Series, Volume 5*, 67–76. [Vidurkinio metinio Kuršių marių vandens balanso klausimu; in Lithuanian].

Dailidienė, I., Davulienė, L., Tilickis, B., Myrberg, K., Stankevičius, A., Paršeliūnas, E. 2005. Investigations of Sea Level Change in the Curonian Lagoon. *Environmental Research, Engineering and Management 4 (34)*, 20–29.

Dailidienė, I., Davulienė, L., Tilickis, B., Stankevičius, A., Myrberg, K. 2006. Sea level variability at the Lithuanian coast of the Baltic Sea. *Boreal Environment Research 11,* Helsinki 24 April, 109–121.

Dailidienė, I. 2007. Changes of hydrological conditions in the Curonian lagoon. *Geographia 43 (1)*, 36–43. [Kuršių marių hidrologinio režimo pokyčiai; in Lithuanian].

Dubra, J., Červinskas, E. 1968. Freshwater balance of the Curonian Lagoon. *Scientific Works of the High Schools, Geography and geology, Volume 5*, 19–26. [Kuršių marių gėlo vandens balansas; in Lithuanian].

Dubra, J. 1978. Water balance. *In* Rainys A. (ed.), *The Curonian Lagoon. Volume II.* Vilnius, 50-70. [Vandens balansas. Kuršių marios; in Lithuanian].

Gailiušis, B., Kovalenkovienė, M., Jurgelėnaitė, A. 1992. Water balance of the Curonian Lagoon. *Energetika 2*, 67–73. [Kuršių marių vandens balansas; in Lithuanian].

Gailiušis, B., Kriaučiūnienė, J. 1999. Modelling of changes of flow velocities fields into Klaipėda strait. *Environmental Research, Engineering and Management 1 (8)*, 18–24. [Klaipėdos sąsiaurio tėkmės planinės struktūros pokyčių modeliavimas; in Lithuanian].

Gailiušis, B., Jablonskis, J., Kovalenkovienė, M. 2001. *The Lithuanian rivers. Hydrography and runoff.* Kaunas, LEI, 792 pp. [Lietuvos upės. Hidrografija ir nuotėkis; in Lithuanian].

Gailiušis, B. 2005. Assessment of the seaport development impact on hydrological regime of the Klaipėda strait. *Environmental Research, Engineering and Management 4 (34)*, 12–19.

Gonenc, I. E., Wolflin, J. P. 2005. *Coastal Lagoons: Ecosystem Processes and Modeling for Sustainable Use and Development*. CRC Press, London, 500 pp.

Hisdal, H., Holmqvist, E., Kuusisto, E., Lindström, G., Roald, L.A. 2004. Has streamflow changed in the Nordic countries? *XXIII Nordic Hydrological Conference,* Tallinn, 8–12 August, 633–643.

Hydrometeorological Service of the Lithuanian SSR. 1960–1989. Hydrological Yearbook. [Gidrologiceskij jezegodnik; in Russian].

Jurgelėnaitė, A., Šarauskienė, D. 2007. The impact of Klaipėda strait permeability on the process of sea water inflow into the Curonian lagoon. *Energetika 53 (2)*, 52–56. [Klaipėdos sąsiaurio pralaidumo pokyčio įtaka jūros vandens prietakos į Kuršių marias procesui; in Lithuanian].

Kjerfve, B., Magill, K. E. 1989. Geographic and hydrographic characteristics of shallow coastal lagoons. *Marine Geology 88*, 187–199.

Kriaučiūnienė, J., Gailiušis, B. 1998. Anthropogenic changes of uneven inflow distribution of the Curonian Lagoon. *Energetika 1*, 19–25. [Kuršių marių prietakos netolygumo antropogeniniai pokyčiai; in Lithuanian].

Kriaučiūnienė, J., Gailiušis, B. 2004. Changes of Sediment Transport Induced by Reconstruction of Klaipėda Seaport Entrance Channel. *Environmental Research, Engineering and Management 2 (28)*, 3–9.

Kriaučiūnienė, J., Meilutytė-Barauskienė, D., Rimkus, E., Kažys, J., Vincevičius, A. 2008. Climate change impact on hydrological processes in Lithuanian Nemunas river basin. *Baltica 21 (1-2)*, 51–61.

Lithuanian Hydrometeorological Service. 1990–2007. Hydrological Yearbook. Vilnius. [Lietuvos hidrometeorologijos tarnyba. Hidrologinis metraštis; in Lithuanian].

Martin, J. L., McOutcheon, S.C. 1999. *Hydrodinamics and transport for Water Quality Modelling: several study*. Florida, CRS Press, 794 pp.

Meilutytė-Barauskienė, D., Kovalenkovienė, M., Irbinska,s V. 2008. Water resources of Lithuanian rivers and their relation to climate change. *Geographia 44 (2)*, 1–8. [Lietuvos upių vandens ištekliai klimato kaitos fone; in Lithuanian].

More, N. H., Slinn, D. J. 1984. The physical hydrology of a lagoon system on the Pacific coast of Mexico. *Estuarine, Coastal and Shelf Science 19*, 413–426.

Nezichovski, R. A. 1975. *Hydrological calculations and forecasting of working regime of reservoirs.* Leningrad, 192 pp. [Gidrologiceskije rascioty i prognozy pri eksplu-ataciji vodochranilisc; in Russian].

Poška, A., Punys, P. 1996. *Engineering hydrology*. Kaunas, 451 pp. [Inžinerinė hidrologija; in Lithuanian].

Reihan, A., Koltsova, T., Kriauciuniene, J., Lizuma, L., Meilutyte-Barauskiene, D. 2007. Changes in water discharges of the Baltic States rivers in the 20th century and its relation to climate change. *Nordic Hydrology 38 (4/5),* 401–412.

Salas, J. D. 1993. Analysis and modelling of hydrologic time series. *In* Maidment D. R. (ed.), *Handbook of Hydrology,* USA, 19.17–19.18.

Spaulding, M. L. 1994. Modeling of circulation and dis-persion in costal lagoons. *In* Kjerfve, B. (ed.), *Coastal Lagoon Processes,* Elsevier Science Publishers, Am-sterdam, 103–132.

Stankūnavičius, G., Žaromskis, R. 2005. Anthropogenic impact as ecosystems regulator in the Curonian Lagoon. *Lagoons and coastal wetlands in the Global change context: impact and management issues, Proceedings of the international conference,* Venice, 26–28 April 2004, 48–55.