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INFLUENCE OF THE KLAIPĖDA SEAPORT DEVELOPMENT ON THE WATER BALANCE OF THE CURONIAN LAGOON

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Abstract. Klaipėda Seaport is near the Klaipėda Strait that joins the Baltic Sea with the Curonian Lagoon. The development of Klaipėda Seaport is implemented by the dredging of the fairway of the Klaipėda Strait and the building of new quays. The dredging of Seaport water territory causes more intensive water interchange between the Baltic Sea and the Curonian Lagoon. It means that more salt water could pass into the Lagoon, which is the biggest fresh water basin in Lithuania. The water balance of the Curonian Lagoon is calculated for the period of 1960-2009 using daily data from 3 meteorological and 11 hydrological measurements stations. The main hydrological elements of water balance of the Lagoon are inflow from the Baltic Sea to the Curonian Lagoon, outflow from the Curonian Lagoon to the Baltic Sea and change in the volume of the Curonian Lagoon. The changes of water balance elements of the Curonian Lagoon were determinated concerning the anthropogenic activity in the Klaipėda Seaport. Statistical methods are used for this study.

Key words: Curonian Lagoon, water balance, hydrological regime, Klaipėda Seaport.

1. Introduction

The Klaipėda Strait that joins the Baltic Sea and the Curonian Lagoon was especially dredged in 1982-1983, when the fairway to the Ferry Terminal on Smeltė peninsula was made (Fig 1). In the beginning of this century the Harbour Entrance reconstruction is completed, Northern part of the Klaipėda Strait is dredged up to 14.0 m, and the fairway dredged up to 12.5 m from the quay No 10 to No 115. Having the same difference of levels between the Baltic Sea and the Curonian Lagoon, the permeability of the Strait used to increase by 10-15% due to anthropogenic activity in the Port. It means that more salt water could pass into the Curonian Lagoon, which is the biggest fresh water basin in Lithuania. Water balance can be assessed as a method allowing determination of water exchange processes in the Lagoon. The water balance method enables us to calculate an element of water balance which can be hardly measured directly (for example, water exchange through the Klaipeda Strait). The water balance of the Curonian Lagoon is calculated for the period of 1960-2009 using daily data from 3 meteorological and 11 hydrological measurements stations. The main hydrological elements of water balance of Lagoon are inflow from the Baltic Sea to the Curonian Lagoon, outflow from the Curonian Lagoon to the Baltic Sea and change in the volume of the Curonian Lagoon. Task of this research is to determine changes of water balance elements of the Curonian Lagoon due to the anthropogenic activity in the Klaipėda Seaport. Statistical methods are used for this study.

2. Methods and data

We calculated the water balance of the Lagoon by the following equation (Gailiušis *et al.* 1992):

$$(Q_U + P - Z) + (Q_J - Q_M) = \pm\Delta V \qquad (1)$$

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

For calculations of river inflow into the Lagoon we used daily discharge data of the Nemunas at Smalininkai, the Šešupė at Kudirka Naumiestis, the Šešupė at Dolgoje, the Šešupė at Marijampolė, 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) (Гидрологический…, 1960–1989; Hidrologinis…, 1990–2009). River inflow calculation methodology was developed using direct data of water measurement stations and methods of analogy for the determination of runoff from those parts of the basin where the runoff was not measured.

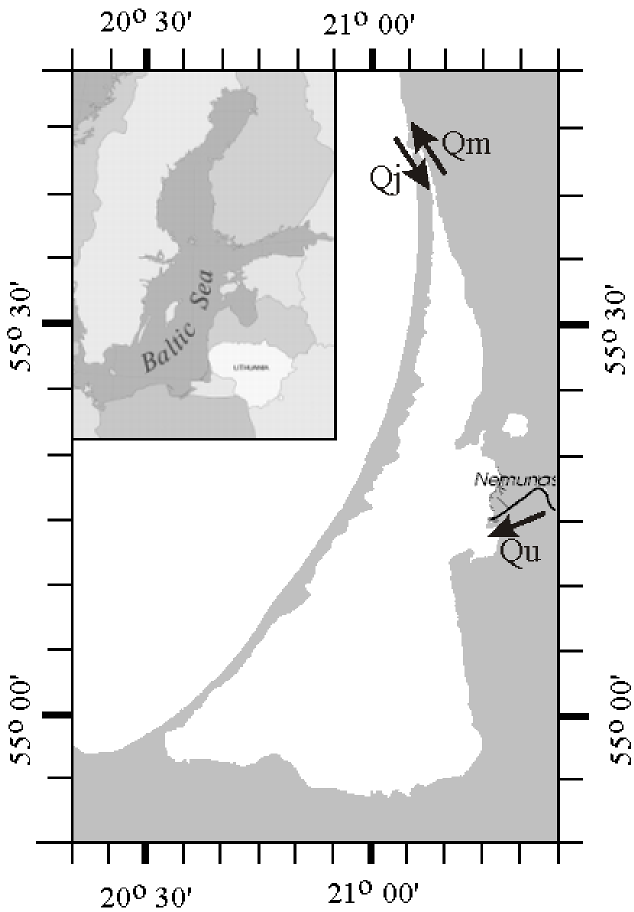

Fig 1. Baltic Sea and Curonian Lagoon

Precipitation in the territory of Lithuania was measured in the meteorological stations (MS) of Klaipėda, Nida and Ventė. Precipitation was calculated for a period of one month. Calculating the input of separate MS into the total amount of precipitation we used the method of Tysen experimental range (Martin and McOutcheon 1999).

Evaporation from the surface of the water of the Lagoon was calculated according to the empirical formula, based on hydrometeorological elements (Gailiušis *et al.* 1992).

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. Data of Juodkrantė hydrological station were used for the evaluation of the water level fluctuations in the Lagoon. According to the dependence of surface water area on water level (Červinskas 1955), and using water level at Juodkrantė, we calculated the surface area of the Lagoon for every day. Having calculated change of the water level (ΔH) and the daily water surface area, we calculated the change in the volume of the Lagoon expressed in discharge ($m^3 s^{-1}$).

The accuracy of average 50-year calculation of water balance depends on the accuracy of calculation of each balance element. Therefore the sum error is calculated as the sum of standard errors of all water balance elements (Gailiušis *et al.* 1992):

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

Where: δ - sum error; δ_1, δ_2, ... , δ_6 - errors of elements of the Curonian Lagoon. If the received balance credibility is equal or lover than sum error $\boldsymbol{\delta}$, then the calculated water balance will be rather accurate.

Significance of trends of water balance elements was evaluated by Mann-Kendall test (Salas 1993). Analysis of significant trends indicates change only in the tendencies of parameters. Non-parametric Mann-Kendall test with a 5% significance level is recommended by the WMO (WMO 1988).

3. Water balance of the Curonian Lagoon in the period of 1960–2009

Water balance of the Curonian Lagoon is calculated during the period of 50 years (Table 1).

Table 1. Water balance of the Curonian Lagoon during the period of 1960–2009 (km^3)

Balance elements	Month												Annual
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
River inflow, (Q_U)	1.937	1.778	2.816	3.580	1.848	1.225	1.141	1.131	1.123	1.418	1.831	1.955	**21.784**
Inflow from sea to lagoon, (Q_J)	0.485	0.322	0.288	0.235	0.327	0.478	0.510	0.550	0.666	0.778	0.899	0.634	**6.171**
Precipitation, (P)	0.088	0.062	0.066	0.059	0.066	0.094	0.120	0.135	0.129	0.140	0.133	0.107	**1.199**
Income	**2.509**	**2.162**	**3.170**	**3.874**	**2.241**	**1.797**	**1.771**	**1.817**	**1.919**	**2.335**	**2.863**	**2.696**	**29.153**
Runoff from lagoon to sea, (Q_M)	2.425	2.272	2.984	3.932	2.299	1.524	1.537	1.668	1.748	2.152	2.542	2.557	**27.642**
Evaporation, (Z)	0.023	0.020	0.031	0.055	0.115	0.155	0.174	0.163	0.119	0.073	0.047	0.032	**1.007**
Losses	**2.448**	**2.292**	**3.015**	**3.988**	**2.415**	**1.679**	**1.711**	**1.830**	**1.867**	**2.225**	**2.589**	**2.589**	**28.648**
Change in 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	**0.061**	**-0.121**	**0.206**	**-0.144**	**-0.252**	**0.095**	**0.092**	**0.001**	**0.075**	**0.085**	**0.320**	**0.051**	**0.468**

The results of this water balance show that sum river inflow is 21.784 km^3 $year^{-1}$, precipitation – 1.199 km^3 $year^{-1}$, and evaporation 1.007 km^3 $year^{-1}$. Water exchange via Klaipėda Strait is the following: inflow water from the Baltic Sea to the Curonian Lagoon – 6.171 km^3 $year^{-1}$ and water runoff from the Curonian Lagoon to the Baltic Sea – 27.642 km^3 $year^{-1}$. We evaluated the sum calculation error of different water balance elements according to the formula (2). The sum error of water balance elements is 0.810 km^3. Calculated error of water balance elements (Table 1) is 0.468 km^3. Therefore, we could state that the water balance is calculated with rather good accuracy.

4. Changes of water balance elements due to the anthropogenic activity in the Seaport

The main elements of water balance are water exchange via the Klaipėda Strait (inflow from the Baltic Sea to the Curonian Lagoon and runoff from the Lagoon to the Sea) and river inflow to the Curonian Lagoon. Some factors have an important influence on water exchange: water level changes of the Sea and the Lagoon, river inflow and the permeability of the Klaipeda Strait. Changes of the river inflow have occurred due to natural cycles of river runoff and climate change (Reihan *et al.* 2007; Kriaučiūnienė *et al.* 2008), also due to anthropogenic activity (Gailiušis and Kriaučiūnienė 1998; Gailiušis *et al.* 1998). These changes are not related to dredging of the Klaipėda Strait. The changes of water level of the Baltic Sea are natural and independent of the activity of the Klaipėda Seaport. Only the permeability of the Klaipėda Strait depends on the development of the Seaport (dredging and construction of new quays).

The history of the Seaport started in the 13th century. The average depths of the Klaipėda Strait were only 5-6 meters until the 19th century and 7-8 meters until the middle of the 20th century.

The voluminous dredging works were done in 1960-1963 when the Strait fairway was dredged to 11 meters. The Klaipėda Strait was especially dredged in 1980-1981, when the fairway to the Ferry Terminal on Smeltė peninsula was made. The Strait fairway was deepened to 12 meters and the permeability of the Strait increased by 10%. The inflow from the Baltic Sea to the Lagoon was calculated for long time period. Two equal periods (1961-1980 and 1981-2000) were selected for evaluation of changes of inflow from the Sea before and after the dredging works. In the period of 1981-2000 the average annual inflow from the Sea was bigger by 1.337 km^3 (24.6%) than in the period of 1961-1980 (Fig 2).

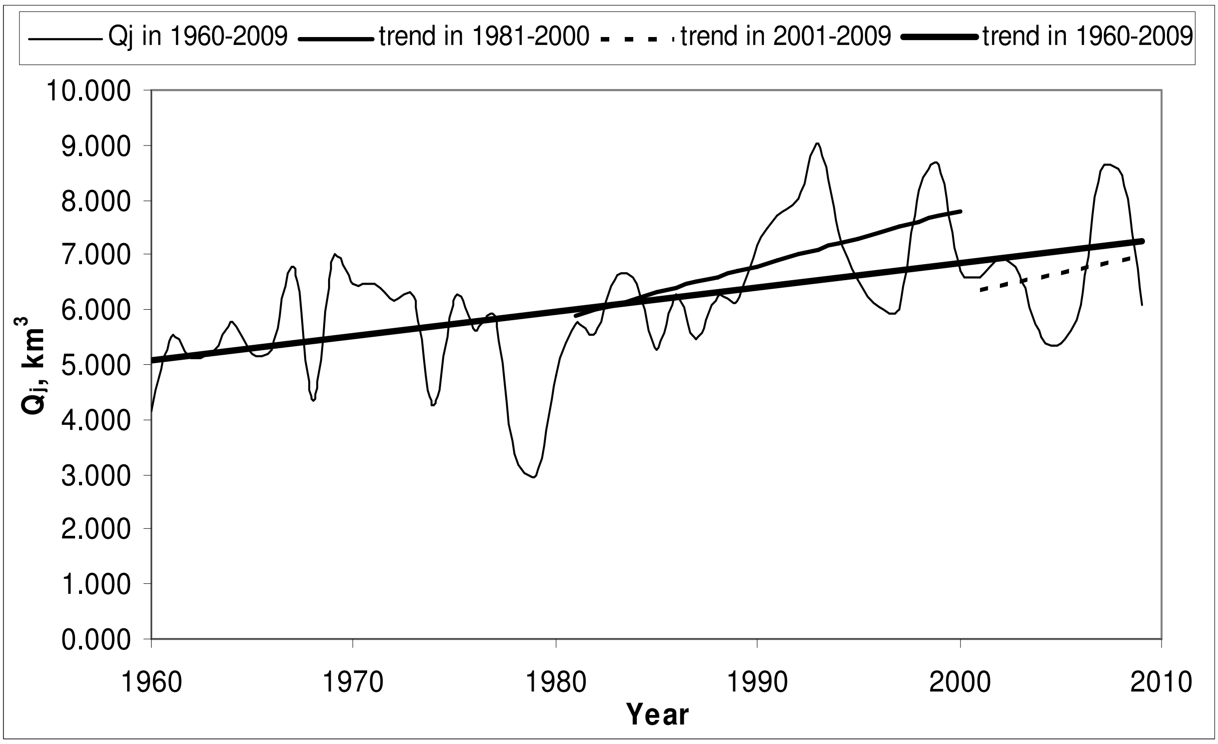

Fig 2. Inflow from the Baltic Sea to the Curonian Lagoon in 1960-2009 and trends for different periods

The probability curves of inflow from the Sea were done for two periods (before and after the dredging of the fairway in 1980-1981). There are a big differences of inflow in these curves (Fig 3) especially for low (to 10%) and high (from 90%) probabilities. For example, inflow of 95 % probability from the Sea after the fairway dredging is 1.77 times bigger than the inflow before dredging.

Trends according to Mann–Kendall test were calculated for inflow from the Sea in the periods before and after the dredging. Insignificant trend was found in the time series of the period 1961-1980 and positive significant trend (probability of 95%) – in 1981-2000.

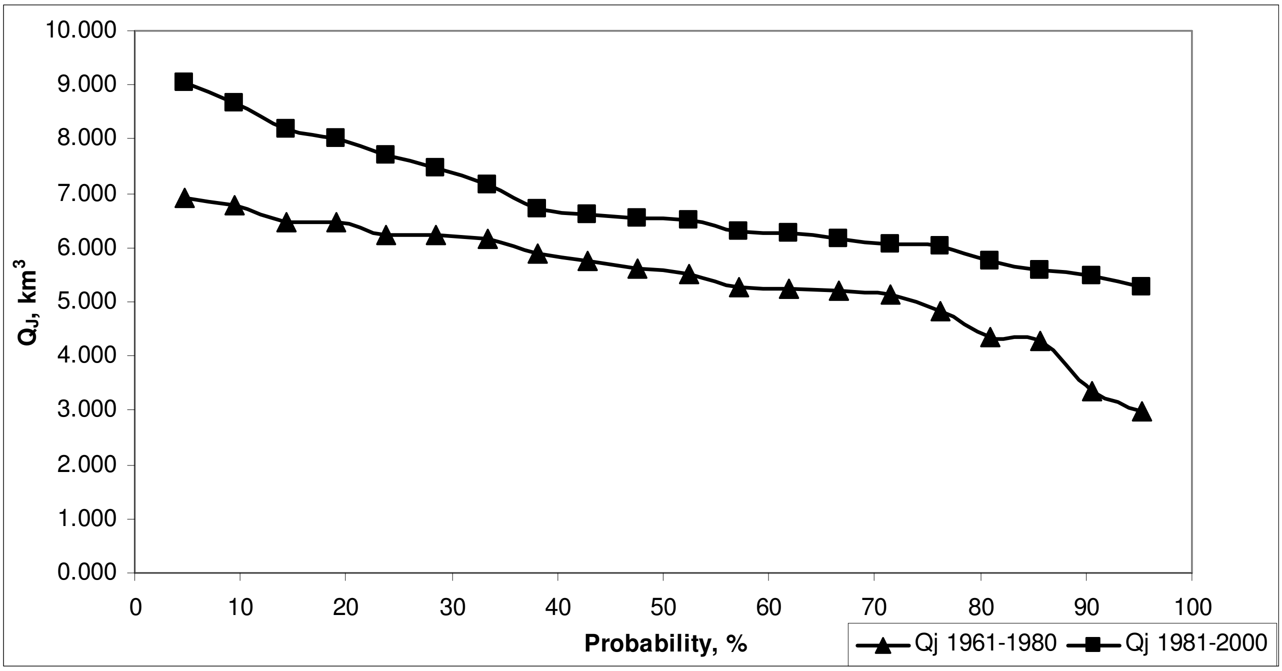

Fig 3. Probability curves of the inflow from the Baltic Sea to the Curonian Lagoon in the periods of 1961-1980 and 1981-2000

In 1998–2002 the Klaipeda Seaport Entrance Rehabilitation Project was carried out including dredging of the northern part of the Strait fairway to 14.5 meters. This implementation increased the permeability of the Klaipėda Strait by 10 %. Another part of Seaport Rehabilitation Project was reconstruction of sea-gate (prolongation of the northern pier of sea-gate up to 202 m and the southern pier up to 278 m). This reconstruction allowed to decrease the permeability of the Strait by 2.5-4% (Gailiušis *et al.* 2004). The reconstruction of the sea-gates partly decreased the increasing of the Strait permeability from 10% to 6-7.5% comparing with the permeability before the Seaport rehabilitation.

Both in 1980-1981 and 2000-2001, after dredging the Seaport, permeability of the Strait increased on the average by 10%. However, in the second period a reconstruction of sea-gates was used to decrease the permeability of the Strait. The influence of this measure is illustrated in Fig 2, where the trend of inflow from the sea in 2001-2009 is flatten (inflow increased on the average by 0.076 km^3 $year^{-1}$) than the trend in 1981-2000 (inflow increased on the average by 0.096 km^3 $year^{-1}$).

It was mentioned earlier that the water exchange through the Strait also depends on the river inflow to the Lagoon and the difference of water levels between the Baltic Sea and the Curonian Lagoon. Therefore, we also analysed the changes of these elements. Cyclic variations are typical of the runoff of the Nemunas River. In the research period, there were two dry phases (1963-1977 and 1991-2006) and one wet phase (1978-1990) of the cycle (Meilutytė–Barauskienė *et al.* 2008). It is difficult to determine a tendency of increase or decrease in river runoff because of cyclic variations, climate change and anthropogenic activity. We calculated that in the period of 1960-2009 the average annual runoff of the Nemunas River in the mouth was 688 m^3/s and increased by 0.49m^3/s $year^{-1}$. We used the same methodology to analyse the changes of water levels at Juodkrantė. It was assumed that the water level at Juodkrantė was the same as the average water level of the Curionian Lagoon. In the period of 1960-2009 the average water level of the Lagoon was 507.8 cm and increased on the average by 2.6 mm per year (the "0" mark of the station is 500 cm). Other researchers determined that the water level of the Baltic Sea increased by 1-1.4 mm per year and the water level of the Lagoon – by 2-4 mm per year (Dailidienė *et al.* 2005). According to study based on sea level data from 155 tide stations world wide, the global mean sea level rise rate is 1.15 mm per year (Emery and Aubrey 1991).

5. Conclusions

Having calculated the water balance of the Curonian Lagoon in the period of 1960-2009, it was determined that the river inflow was 21.784 km^3 $year^{-1}$, precipitation was 1.199 km^3 $year^{-1}$, and evaporation was 1.007 km^3 $year^{-1}$. The salt and fresh water exchange through the Klaipeda Strait consisted of inflow of salt water from the Baltic Sea to the Curonian Lagoon, which was 6.171 km^3 $year^{-1}$, and fresh water runoff from the Curonian Lagoon to the Baltic Sea, which was 27.642 km^3 $year^{-1}$.

After every dredging of the Strait, its permeability increased on the average by 10%, if no measures to decrease the influence of dredging are taken, and by 6-7.5%, if the technical measures (sea-gate reconstruction, new quays) are used.

The variations of water exchange through the Klaipėda Strait depend on many factors. The water level of the Curonian Lagoon in the period of 1960-2009 increased by 2.6 mm per year, while the water level of the Baltic Sea increased by 1-1.4 mm per year. The river inflow to the Lagoon increased by 0.49$m^3/s\ year^{-1}$ in the same period. Also, the permeability of the Strait changed because of development of the Klaipėda Seaport. It is difficult to determine the influence of separate elements to the water exchange because of complexity of the system Nemunas River - Curonian Lagoon - Baltic Sea.

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