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# Dynamics of the Nemunas River delta front during the period 1910–2005

***Donatas Pupienis, Gintautas Žilinskas, Darius Jarmalavičius, Jonas Satkūnas***

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**Abstract** An analysis of changes in the coastline of the Nemunas River delta front was undertaken with GIS based on cartographic material representing a 95 year period. Delta development was analysed comparing two time periods: 1910–1958 and 1958–2005. Quantitative indicators of land area determined during the study indicate that land in the northern part of the Nemunas delta front decreased more than 2.1 times in the 1958–2005 period, compared to the previous 1910–1958 period. The main reasons for the decrease of sediment accumulation are a decrease Nemunas River runoff, and a similar decrease of sediment particulates, due to anthropogenic activity and natural factors a rise in the water levels of the Baltic Sea and the Curonian Lagoon, as well as land subsidence in the Nemunas delta region.

***Keywords*** *Nemunas delta front (avandelta) • Runoff • Sedimentation • Inundation • Sea level rise • Lithuania*

*Donatas Pupienis [donatas.pupienis@gf.vu.lt], Jonas Satkūnas, [jonas.satkunas@lgt.lt], Vilnius University, Čiurlionio 21, 03123 Vilnius, Lithuania; Gintautas Žilinskas, [zilinskas@geo.lt], Nature Research Centre, Institute of Geology and Geography, Ševčenkos 13, 03223 Vilnius, Lithuania / Institute of Maritime and Cultural Landscapes, Klaipėda University, H. Manto 84, 92294 Klaipėda, Lithuania; Darius Jarmalavičius [jarmalavicius@geo.lt], Nature Research Centre, Institute of Geology and Geography, Ševčenkos 13, 03223 Vilnius, Lithuania.* *Manuscript submitted 21 December 2011; accepted 26 April 2012.*

## INTRODUCTION

Rapid changes in hydrographic networks and in coastal delta fronts cause many problems relating to navigation, fishing, flooding of coastal infrastructure (Frihy,1992; Chen *et al.* 2005; Syvitski *et al.* 2009), and even delimitation of state borders (Žilinskas, Jarmalavičius 2001). These problems are constrained by rising sea level that will cause flooding of coastal lowlands and deltas and will severely impact ecosystems (Frihy 1992; Allison 1998; Dixon *et al.* 2006; Mikhailov, Mikhailova 2006; Bindoff *et al.* 2007; Syvitski 2008). This in turn will negatively impact living conditions for inhabitants of deltas (Ericson *et al.* 2006; Overeem, Syvitski 2009). At first water salinity will increase, and later on during storms, deltas will be inundated and more severely eroded (Ericson *et al.* 2006).

The Nemunas delta is very important due to its natural landscape, ecosystem values, and economic value. Like most of the deltas in the world (Sostoa, Sostoa 1985; Ibańez *et al.* 2000; Syvitski, Saito 2007; Vörösmarty *et al.* 2009) the Nemunas delta is also well known for its great biodiversity. In 1992 the Nemunas Delta Regional Park was established in order to preserve its original landscape, and natural and cultural heritage.

Investigations of the structure and dynamics of the Nemunas delta were started by G. Berendt (1869) in the second half of the 19th century. M. Grigat (1931) was the first who carried out a comprehensive description of the geomorphological–palaeogeographical conditions of the Nemunas delta. Since then the problems of geology, physical geography and dynamics of sedimentation of the Nemunas delta have been analysed by a number of researchers (Gudelis 1955; Kabailienė 1959; Basalykas 1961; Kunskas 1982; Žilinskas, Jarmalavičius 2001; Bitinas *et al.* 2002; Vaikasas, Rimkus 2003).

Despite considerable attention of researchers there are very few works dealing with the dynamics of the Nemunas delta front in time and space. Data on the dynamics of the Nemunas delta front, based on analysis of old cartographic materials, were published by E.

Scofield (1938), J. Petrulis (1968). However, data on the more precise quantitative characteristics of delta dynamics became available only after the analysis of much more detailed maps compiled in the 20th century. Changes in the Nemunas delta front during the first half of the 20th century were analysed by M. Beconis (1967) and E. Červinskas (1972), and changes in the delta front during the longer period 1910–1993 were studied by G. Žilinskas and D. Jarmalavičius (2001).

The development evolution of the Nemunas delta front during the years 1910–2005 has been analyzed on the basis of historical maps, orthophoto digital map and hydrological data (Curonian Lagoon water level, Nemunas River runoff). The aim of this paper is to estimate the shoreline changes of the Nemunas delta front in 20–21 centuries.

## STUDY AREA

The Nemunas River is the largest river in Lithuania, its headwater is in Belarus (approximately 45 km south of Minsk), and its total length is 937.4 km (359 km in the territory of Lithuania, 462.4 km in Belarus and 116 km at the boundary of Lithuania with Belarus and Russia) (Gailiušis *et al.* 2001). The Nemunas catchment area is 97 863.5 km$^2$ of which 46 695.4 km$^2$ occurs in Lithuania (equal to 72% of the territory of Lithuania). The Nemunas has about 215 tributaries (Gailiušis *et al.* 2001) and flows to the Curonian Lagoon, which has an area of 1554.5 km$^2$, of which the Lithuanian part is 381.6 km$^2$ (Žilinskas, Petrokas 1998). The volume of water of the Curonian Lagoon is approximately 6.2 km$^3$ (Červinskas 1959). An average depth is 3.8 m (maximum depth 5.8 m), however, in the Klaipėda Strait (in the Klaipėda port) in some courses of fair way and by embankments depths are up to 14.0–14.5 metres (Gailiušis *et al.* 1996, 2005). The area of catchment of the Curonian Lagoon is 100 458 km$^2$, 98% of which is in the Nemunas catchment (Gailiušis *et al.* 2001).

Geoscientists dealing with deltas admit that the most difficult task is to define the boundaries of deltas (Žaromskis 1999; Syvitski 2008). V. Gudelis (1987, 3 p.) reports that: *"the recent Nemunas delta includes that part of the Lithuanian coastal plain with the sedimentary–alluvial cover and main relief trails which were developed by Nemunas (with branches) and adjoining deltas of other rivers. The process started with the flood accumulation of alluvium and formation of organogenic complexes (peat, sapropel, etc.)"*. According to the above statement the generation of the recent Nemunas delta coincides with the development of the Litorina Sea or the beginning of the Atlantic period (about 8000–7500 BP).

The starting area point for the continental Nemunas delta is the place where the mouth divides into two main branches: the right one – Rusnė and the left one – Gilija. The Gilija (43 km long) flows through the Kaliningrad Oblast of Russia to the Curonian Lagoon (Fig. 1A).

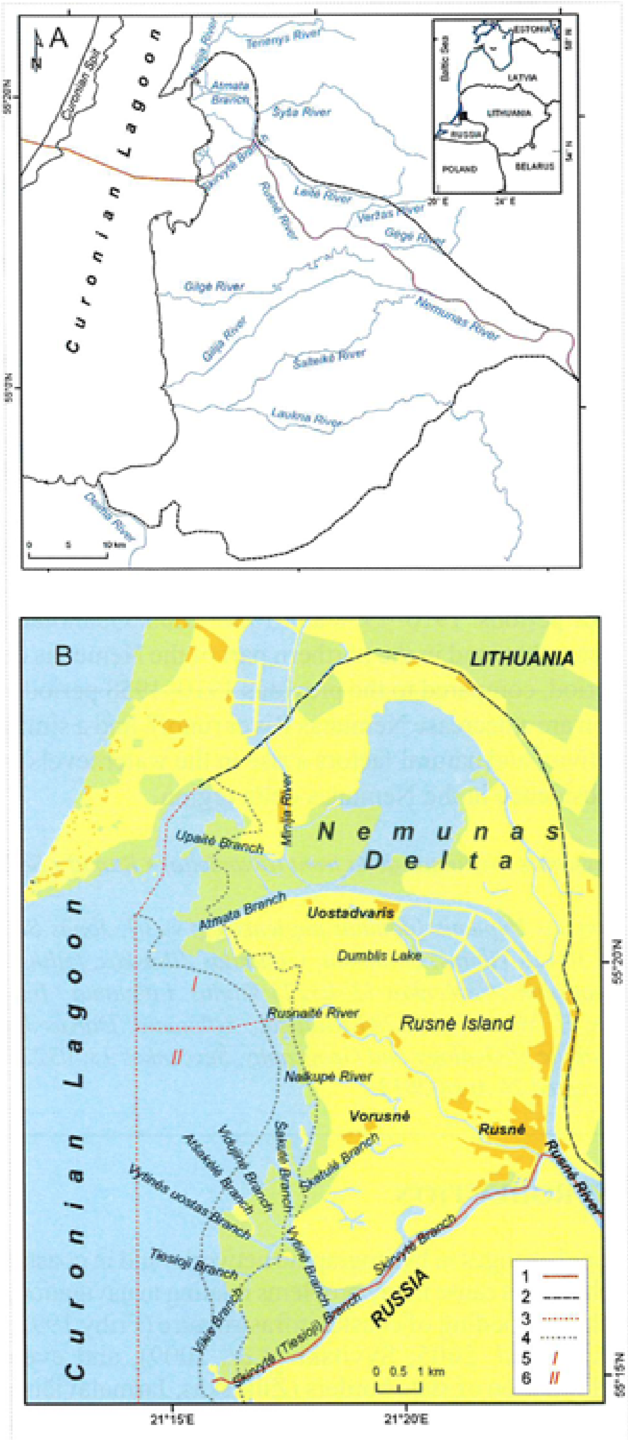


**Fig. 1** A – the location of the Nemunas River delta and its boundary according to V. Gudelis (1987, 1998). B – the Nemunas River delta in Lithuania. 1 – state boundary, 2 – limit of the Nemunas delta in Lithuania, 3 – limit of sector, 4 – limit of the Nemunas River delta-front according to V. Gudelis (1998) and R. Žaromskis (1999), 5 – the Atmata mouth sector, 6 – Skirvytė's branches sector. Compiled by D. Pupienis, 2012.

Near the Rusnė settlement (which is 13.2 km landward than the river mouth) the second left branch (the Skirvytė) separates from the Rusnė and flows south–westerly (Table 1). The state border between

**Table 1** The river and branche names in the Nemunas delta. Compiled by D. Pupienis, 2012.

| Lithuanian | German | Russian (after 1945) |
|---|---|---|
| Atmata | Atmath | Atmata (Атмата) |
| Atšakėlė | – | – |
| Deimena* | Deime | Dajma, Dejma (Дейма) |
| Gėgė* | Gäge (1785) | – |
| Gilija* | Gilge | Matrosovka (Матросовка) |
| Laukna* | Laukne | Rzhevka (Ржевка) |
| Leitė* | Leithe | – |
| Minija* | Minge | – |
| Naikupė* | Neikopp, Neucupe | – |
| Nemunas* | Memel | Neman (Неман) |
| Nemunynas* | Nemonien | Zlaya (Злая) |
| Pakalnė* | Pokallna | – |
| Rindos šaka | – | – |
| Rusnaitė* | Russneit | – |
| Rusnė* | Russ | Neman (Неман) |
| Šakutė* | Szakutt | – |
| Šalteikė* | Schalteik | Nemoninka (Немонинка) |
| Skatulė* | Skatull | – |
| Skirvytė* | Skirwieth | Severnaya (Северная) |
| Skirvytė (Tiesioji) * | Gerade-Ost | – |
| Šyša* | Schiesche | – |
| Tenenys | – | – |
| Upaitė* | Dobe Upeit | – |
| Veržas* | Warsze | – |
| Vidujinė | – | – |
| Vikis | – | – |
| Vorusnė* | Warruß | – |
| Vytinė* | Wietinn | – |
| Vytinės uostas | – | – |

* Rivers and rivulets in the Nemunas delta, which names have been in use throughout the XIX and XX centuries (after Pėteraitis, 1992).

Lithuania and Russia is located along the fairway of the Skirvytė. The Skirvytė River (length 9.7 km) is the second branch of the Nemunas delta from the left side. The Skirvytė River has a number of branches: Pakalnė, Rusnaitė, Vytinė, Šakutė, Vidujinė, Atšakėlė, Vytinė uostas, Tiesioji, Vikis (Fig. 1B). Beween the Rusnaitė and the Skatulė the shallow stream Naikupė flows. The part of the Skirvytė which separates from the Vytinė is named the Skirvytė Tiesioji. At the mouth there are several small nameless branches that break away. There is no data on how the water proportionately distributes to all these branches of the (except for Pakalnė where 2–6% of water volume of the Skirvytė runoff), however, morphometric measurements (Žilinskas, Jarmalavičius 2001) indicate that the main course of the present runoff should pass through Skirvytė Tiesioji. The Skirvytė's branches delta front (avandelta) sector stretches from the Rusnaitė River in the north to the Skirvytė River in the south (Fig. 1B).

The second branch of the Rusnė River, after its embranchment, turns to the north–west and is named the Atmata. The Atmata River flows around Rusnė Island and near Uostadvaris it joins the Minija River and 3 km further downstream it flows into the Curonian Lagoon. The overall length of the Atmata River is 12.6 km. The Atmata since the 19$^{th}$ century has been maintained for shipping purposes, the banks has been reinforced and its mouth regularly dredged. The northern part of the delta front of Atmata is crossed by the Upaitė (length is 21.5 km) the right-hand branch of the Minija River (Fig. 1B). The Atmata delta front sector stretches from the Kniaupas Bay in the north to the Rusnaitė River in the south (Fig. 1B).

From the point of view of dynamics at present it is possible to distinguish two parts of the Nemunas delta front: the passive southern Deima – Skirvytė (Russian part) and active northern Skirvytė – Atmata (Lithuanian part) (Fig. 1B). The coast of the Curonian Lagoon in the southern part of the delta is stabilized in many places as a result of considerable reduction in transport of alluvial material. The recent Nemunas delta is a lagoon blocked, tideless, multi-branched and multi-mouthed delta with a straightened contour (shoreline). The area of the Nemunas delta is 2000 km$^2$, the size of northern part belonging to Lithuania is 662 km$^2$ (Basalykas 1965).

## MATERIAL AND METHODOLOGY

In the paper, water-level measurement data was used from Klaipėda (1910–2005) and Nida (1925–2005) hydrological stations. The analysis of the Nemunas River runoff was based on the data from Smalininkai hydrological station (1910–2005 m.). The water-level measurement data were obtained from the Department of Marine Research, Klaipėda and the Nemunas River run-off data – from archives of the Lithuanian Hydrometeorological Service. The Klaipėda and Nida's water-level trends and the Nemunas runoff trend were determined for two different time periods, i.e. 1910–1958 and 1959–2005. The statistical significance ($\alpha < 0.05$) of the tendencies was determined using the non-parametric Mann–Kendall test.

One of the most effective ways of studying the dynamics of the Nemunas delta front is by the comparative analysis of cartographic material using GIS tools. In this paper the delta front is regarded as *the frontal and most active part of the delta with islands*. The Nemunas delta front margin in the lagoon corresponds to 2 m isobath (Gudelis 1998), in the mainland (onshore) corresponds to the youngest part of the Nemunas delta area (Žaromskis 1999), it is the position of the shoreline at the beginning of the 20$^{th}$ century (see Fig. 1). The data of delta front change can be investigated through the time-series comparison of various data sets that include historical photographs, topographic maps and charts, aerial photography, beach surveys, *in situ* geographic positioning system shorelines, and a range of digital elevation or image data derived from remote sensing platforms (Boak, Turner 2005).

According to V. Gudelis and S. Kazakevičius (1998) each of the topographic maps has some plane errors which means that the point plotted on the map does not necessarily corresponds to the same point on the ground. The error on a map at a scale of 1:25 000 is $\delta$ (x) = ±12.5 m (Gudelis, Kazakevičius 1998) and therefore it is possible to determine dynamics of the delta front contours and other traceable features with adequate accuracy. Historical topographic maps and orthophoto digital map of different periods were used for comparative analysis of the dynamics of the Nemunas delta front (Table 2).

**Table 2** Cartographic materials applied to analyse the dynamics of the Nemunas delta front from 1910 to 2005. Compiled by D. Pupienis, 2012.

| Source | Year | Executive agency | Coordinate system | Map scale |
|---|---|---|---|---|
| Topographic map | 1910 | German Cartographic Survey | Ferro on Bessel 1841 ellipsoid | 1:25 000 |
| Topographic map | 1958 | Agency for Geodesy and Cartography of the USSR | Gaus-Krüger on Krasovski 1940 ellipsoid | 1:25 000 |
| Orthophoto digital map | 2005 | National Land Service of the Republic of Lithuania | LKS-94 on GRS80 ellipsoid | 1:10 000 |

According to E. Červinskas (1972) the cartographic maps published in 1910 were compiled using precise instrumental field measuring and triangulation method, and applying correction based on old Germany topographic maps. Therefore, in this work the changes in Nemunas avandelta were analyzed from 1910. Prior to digitizing, all charts used in this study were georeferenced and transformed to the same Lithuanian national geographical reference system (LKS–94) based on standard Transverse Mercator projection with ESRI ArcGIS 9.3.1 software using angular coordinate and fixed points for each chart. The overlapping was possible as the positions of the fixed points, such as lighthouses, flag-tower and church were located on old maps.

On the basis of georeferenced topographic maps and orthophoto digital map the coastline layer was created. The changes of the shifting coastline of the Nemunas delta front during the periods of 1910–1958, 1958–2005 and 1910–2005 were assessed with Spatial Statistics tools. The following periods 1910–1958, 1958–2005 were chosen because both are rather equal in duration: 48 and 47 years, respectively. On the other hand, when analysing delta front changes during shorter time periods, the problem of temporal, short-period events arises. A review of cartographic materials of different years shows that essential changes of the delta front began in 1959 after the construction of the Kaunas hydroelectric power plant, exploitation of which initiated regulation of runoff of the Nemunas River.

## RESULTS

In the case when the Nemunas runoff is medium (541 $m^3/s$) or close to it, approximately 1/5 of the Nemunas runoff falls on Gilija and 4/5 of the Nemunas runoff falls on Rusnė (Table 3). When the Nemunas River runoff is exceeded by 1000 $m^3/s$, the Nemunas and Rusnė at lower sites overflow their banks, whereas Gilija does not even during major floods. In the case when the floods begin in the Nemunas the Gilija's attributable part of the Nemunas runoff decreases by 10%, while Rusnė's respectively increases by the same amount (Rainys 1991). Taking into account the Nemunas River runoff distribution it can be stated that the major changes in the Nemunas delta front take place in the active northern Skirvytė—Atmata area (Lithuanian part).

**Table 3** The Nemunas River flow distribution between Gilija and Rusnė branches, in numerator – a maximum flow rate, in denominator – an average flow rate. Compiled by D. Pupienis, 2012.

| Run-off | | | | | | Method | Author |
|---|---|---|---|---|---|---|---|
| Nemunas River | | Rusnė Branch | | Gilija Branch | | | |
| Q, $m^3/s$ | % | Q, $m^3/s$ | % | Q, $m^3/s$ | % | | |
| 6450 / 580 | 100.0 / 100.0 | 5650 / 470 | 87.6 / 81.0 | 800 / 110 | 12.4 / 19.0 | Measured | Keller, 1899 |
| 6729 / 613 | 100.0 / 100.0 | 6100 / 500 | 90.6 / 81.6 | 629 / 113 | 9.4 / 18.4 | Unknown | Kolupaila, 1940 |
| 4080 / 680 | 100.0 / 100.0 | 3505 / 508 | 85.9 / 74.7 | 575 / 172 | 14.1 / 25.3 | Calculated | Macevičius, 1972 |
| 4530 / 680 | 100.0 / 100.0 | 3960 / 528 | 87.4 / 77.6 | 571 / 152 | 22.4 / 12.6 | Calculated | Rainys, 1991 |

In the period since the 18th century until the 20th century Atmata was the main course of the Rusnė causing Skirvytė less significant. According to T. Rumland and H. Lippke (1908) Atmata was the main stream supplying a major part of the Rusnė runoff and drift matter transportation during spring floods (Table 4). The sediments have been accumulating in the coastal zone of the Curonian Lagoon, filling up channels and

**Table 4** The Rusnė River runoff distribution into the branches and valley at the Rusnė hydrological stations during flood. Compiled by D. Pupienis, 2012.

| Rusnė river water level | Branches Runoff | | | | | | | | Method | Author |
|---|---|---|---|---|---|---|---|---|---|---|
| | Rusnė | | Skirvytė | | Atmata | | Atmata Valley | | | |
| | Q, m³/s | % | Q, m³/s | % | Q, m³/s | % | Q, m³/s | % | | |
| – | 6100 | 100.0 | 1650 | 27.0 | 1897 | 31.1 | – | – | Measured | Rumland and Lippke, 1908 |
| 4.09 | 6100 | 100.0 | 3605 | 59.1 | 1897 | 31.1 | – | – | Calculated | Kolupaila, 1933 |
| 3.20 | 1920 | 100.0 | 1150 | 59.7 | 770 | 40.3 | – | – | Calculated | Macevičius, 1972 |
| 2.40 | 4220 | 100.0 | 2420 | 57.3 | 920 | 21.8 | 880 | 20.8 | Measured | Vaikasas, 2009 |
| 3.05 | 7500 | 100.0 | 3950 | 52.7 | 1500 | 20.0 | 2050 | 27.3 | Modeled | Vaikasas, 2009 |

forming islands. The Atmata was moving forward and its mouth reached and captured the Minija River, which previously falling directly into Curonian Lagoon (Červinskas 1972; Žilinskas, Jarmalavičius 2001). At the time when the length of the Atmata was extending, the inclination of the stream bottom was declining causing reduction in the amount of drift matter being transported (Červinskas 1972). The accumulation of sediments in the Atmata resulted in the shallows and islands formation (see Figs 2, 3). As a result of reduction in runoff of the Atmata (Kolupaila 1933) more water

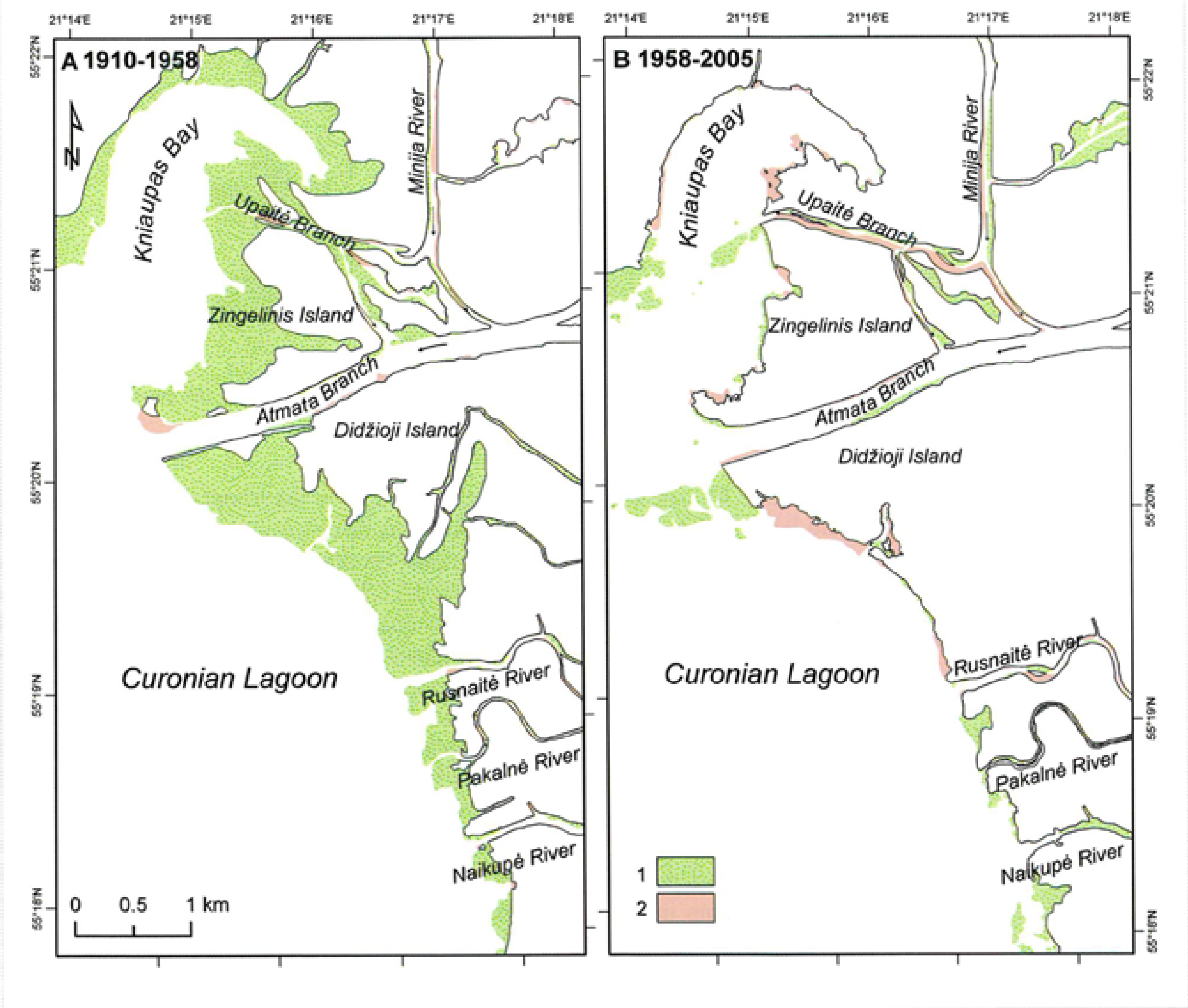


**Fig. 2** Dynamics of the Atmata River mouth in the period 1910–1958 (A) and in the period 1958–2005 (B). 1 – accumulation, 2 – erosion. Compiled by D. Pupienis, 2012.

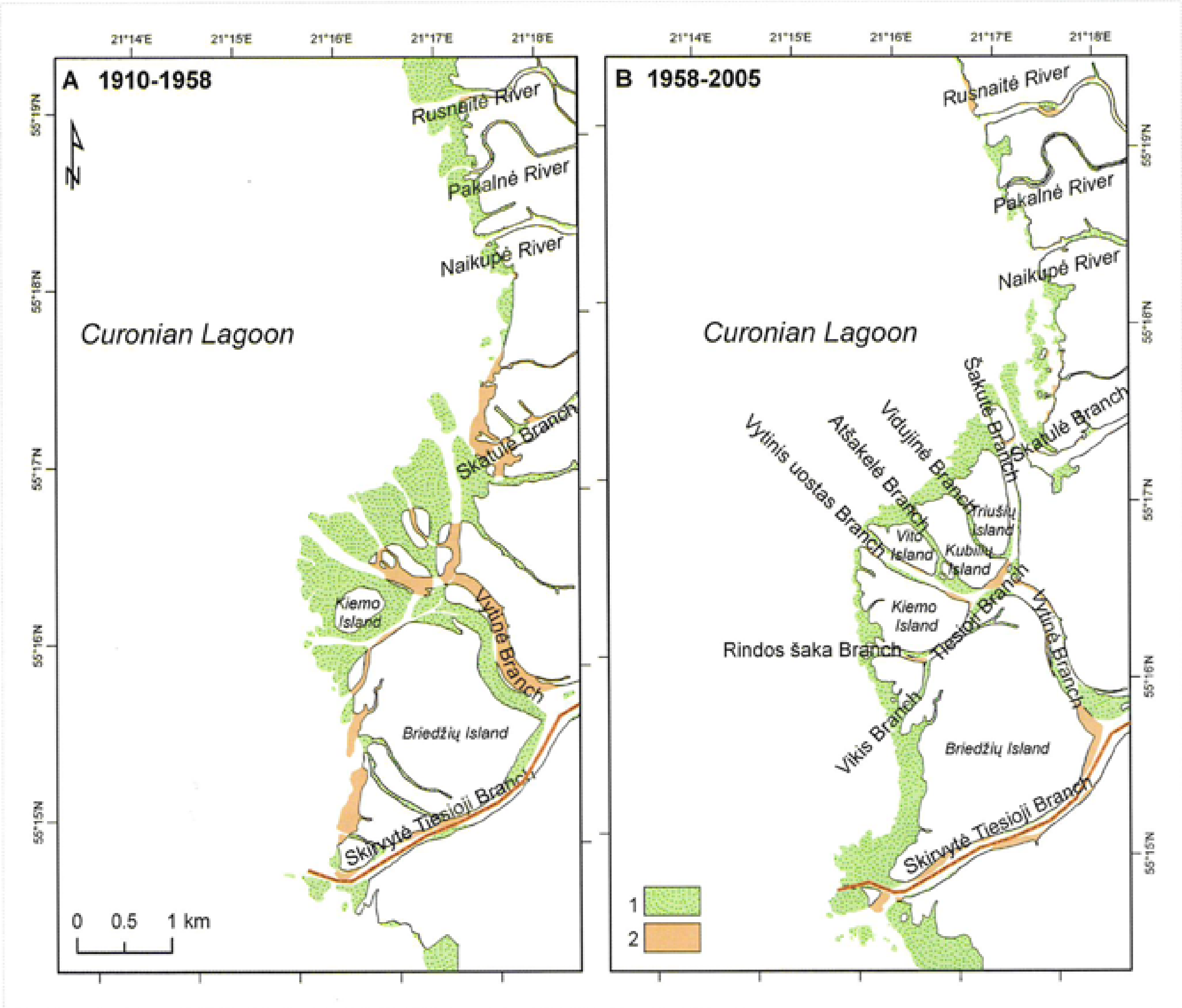


**Fig. 3** Dynamics of the Skirvytė's branches delta front sector in the period 1910–1958 (A) and in the period 1958–2005 (B). 1 – accumulation, 2 – erosion. Compiled by D. Pupienis, 2012.

started to flow down the Skirvytė (Table 4), causing the formation of the large Briedžių Island (Fig. 3) by joining shallow accumulations of sediment. The island caused a separation of the Skirvytė River into two branches: Skirvytė Tiesioji and Vytinis (Fig. 3). At the beginning of the 20th century the annual average runoff of Skirvytė was almost equal to the Atmata's runoff (Table 4). By the end of the 20th century the annual average runoff of the Atmata was 21.8%, whereas the runoff of Skirvytė was 57.3% of the total Rusnė River runoff (Vaikasas 2009).

At present the delta front of the Skirvytė is nearly twice as large as the delta front of the Atmata (Fig. 2). According to the rates and characteristics of development, there are two distinguishable sectors in the northern part of the Nemunas delta front: 1) the Atmata delta front and 2) the Skirvytė's branches delta front (Fig. 1). As these sectors are characterized by individual peculiarities of development, it is appropriate to discuss them separately.

Analysing changes of the Atmata delta in the period 1910–1958 it was discovered that during this period the mouth of the Atmata was moving towards Curonian Lagoon (Fig. 2A). In the 48 year period addressed to this study the coastline in the Kniaupas Bay moved 100–150 m towards the lagoon, the coastline at the mouth of the Upaitė moved 420–445 m, and the coastline at the mouth of the Atmata moved up to 620–700 m. In the same time period the area of Zingelinis Island – on the north side of the Atmata mouth – expanded more than twice (from 0.98 km$^2$ up to 2.05 km$^2$). Sediment accumulation in the southern part of the Atmata delta front was much more intensive during the period under consideration. The Didžioji Island (Fig. 2A) land area increased by 2.09 km$^2$ (the shoreline advanced into the lagoon by 1050 m). In the sector between the Kniaupas Bay and the Rusnaitė River mouth the coast advanced by 100–1050 m (from 1910 to1958) and the land area increased by 4.64 km$^2$ (Table 5).

**Table 5** Measured changes in the Atmata delta front sector in the period 1910–2005. Compiled by D. Pupienis, 2012.

| Variation of delta front | 1910–1958 | | 1958–2005 | | 1910–2005 | |
|---|---|---|---|---|---|---|
| | Total, km² | Annual, km²/year | Total, km² | Annual, km²/year | Total, km² | Annual, km²/year |
| Increase of land area | 4.84 | 0.10 | 1.08 | 0.02 | 5.92 | 0.06 |
| Erosion of land area | 0.20 | 0.01 | 0.65 | 0.01 | 0.85 | 0.01 |
| Total change of land area | 4.64 | 0.01 | 0.43 | 0.01 | 5.07 | 0.05 |

During this period coastal erosion occurred in those places where the Atmata channel was dredging (Červinskas 1972). During storms material from the delta front was moved along the coast. As the prevailing wind direction is west and south–west, the sediments, due to complex systems of circular currents, were moving south–easterly and north–easterly from the mouth of the Atmata (Červinskas 1959; Davulienė *et al.* 2002; Ferrarin *et al.* 2004). The largest accumulation of sediment took place in the Atmata mouth and the rate of accumulation decreased to the north and south of mouth respectively. In the same time period of 1910–1958 in the Kniaupas Bay the sediments contributed by the Upaitė River and the Minija River, was much lower and relatively insignificant (Kolupaila 1940) (Fig. 2A). Due to the fact that little sediments are carried by Upaitė and Minija river to the Kniaupas Bay, the main deposits here are those of organic origin (broken shells, plant remains) (Červinskas 1972; Bitinas *et al.* 2002).

During the second half of the 20th century and the beginning of the 21st century the intensive accumulation in this Atmata River mouth sector begun to slow down and in some river courses erosion processes begun to prevail. For example, in the period 1958-2005 the coastline at the mouth of the Upaitė receded approximately 70 m, and erosion processes occupied the southern part of the Atmata mouth area. In some places the coastline of the Didžioji Island receded by up to 100 m (Fig. 2B). Zingelinis Island shoreline moved by about 50 m, and Didžioji Island by 270 m towards Kniaupas Bay (Fig. 2B). These island enlargements were directly linked to the channel dredging, not to natural accumulation of sediments, as sand from the deepened channel was distributed on both sides of the Atmata channel mouth. According to Inland Waterways Direction of Lithuania in the period 1995–2005 approximately 323 010 m³ of sediments was dug from the Atmata channel mouth. It is worth noting that the main purpose of the Atmata channel deepening is to increase water stream during floods, and thus to decrease flood hazard near the Rusnė and Uostadvaris settlements and surrounding villages during spring flooding and to increase the movement of river ice. Another purpose like maintaining shipping conditions is of less importance because the flat-bottom boats used require only 1.5 m depth. In the study period of 1958–2005 the total area of land between the Kniaupas Bay and the Rusnaitė River expanded by 0.43 km².

Analysis of the changes of the Skirvytė's branches delta front during the years 1910–1958 has shown that its mouth and the mouths of its branches were rapidly moving towards the Curonian Lagoon (Žilinskas, Jarmalavičius 2001) (Fig. 3A). The mechanism of Skirvytė's branches avandelta expansion differs from that of the Atmata mouth. As a result of shallow near shore depths (at a distance of 300 m into the lagoon the depth is 1.0 m) the sediments, carried by the branch streams, settle beyond the river mouth on both sides of the fairway (Žilinskas, Jarmalavičius 2001). Skirvytė runoff results in the circulation of anticlockwise gyre on the northern site of the Skirvytė River and on southern site – clockwise gyre, causing sedimentation on both sides (Červinskas 1959; Davulienė *et al.* 2002). Since the sediments are not carried far into the lagoon, a large number of islands have begun to develop in the river mouth.

In the northernmost part of the Skirvytė's branches delta front in the period 1910–1958 low runoff in the Rusnaitė, Pakalnė, Naikupė branches, and other smaller rivers (Kolupaila 1933; Macevičius 1972), resulted in the sediment accumulation processes much less intensive compared to the accumulation around the Atmata mouth (Červinskas 1972). On both sides of the mouths of the Rusnaitė and Pakalnė branches the coastline continued to move into the lagoon – 340 and 325 m, respectively. The coastline at the mouth of the Naikupė moved only about 50–120 m into the lagoon (Fig. 3A). In the same period the coast at the mouth of the Skatulė was eroded and retreated approximately 76 m.

Particularly distinctive changes took place in the Vytinė branch where the number of islands from 1910 had increased from three to five by 1958. In that time period the area of islands formed by the Vytinė branch increased by 1.68 km² and the land advanced into the lagoon by 210–675 m. However, during this time the greater part of Briedžių Island was eroded and in some places the coastline retreated up to 100 m. The total area of Skirvytė's branches delta front expanded in 1910–1958 by 2.29 km² (Table 6).

Between 1958–2005 the accumulation processes in the coastline sector between Rusnaitė and Naikupė continued to slow down and the coastline advanced into the lagoon on average of 18 m. However, a considerable increase in accumulation was observed in the southern part of this course (Fig. 3B). Several promontories longer than 1 km formed to the north from the Skatulė mouth, in the area of coastline which previously tended to be eroded. During this period Vytinė and its branches became shallow, water runoff decreased and the

**Table 6** Measured changes in the Skirvytė's branches delta front sector in the period 1910–2005. Compiled by D. Pupienis, 2012.

| Variation of delta front | 1910–1958 | | 1958–2005 | | 1910–2005 | |
|---|---|---|---|---|---|---|
| | Total, km$^2$ | Annual, km$^2$/year | Total, km$^2$ | Annual, km$^2$/year | Total, km$^2$ | Annual, km$^2$/year |
| Increase of land area | 3.53 | 0.07 | 3.12 | 0.07 | 6.65 | 0.07 |
| Erosion of land area | 1.24 | 0.03 | 0.40 | 0.01 | 1.64 | 0.02 |
| Total change of land area | 2.29 | 0.05 | 2.72 | 0.06 | 5.01 | 0.05 |

amount of transported matter decreased respectively (Vaikasas 2009). All these caused the slowdown in land expansion resulting in only 55–110 m advance of the coastline into the lagoon. When the increasing volume of water moved to Skirvytė Tiesioji, the delta front advance towards the lagoon became more active in the southern part of the delta (Fig. 3B). The north coastline of the mouth of the Skirvytė moved towards the lagoon by about 550 m, while to the south of the mouth the movement was only 110 m. Thus, in the period 1958–2005 the largest land area accumulation measured in the whole of the Nemunas delta front was around the Skirvytė River mouth. The total area of the Skirvytė's branches delta front expanded by 2.72 km$^2$ (Table 6). During the second part of 20$^{th}$ century and beginning of 21$^{st}$ century (1958–2005) the area in this sector increased by 1.2 times.

The cartographic analysis has shown that during the first part of 20$^{th}$ century the most intensive accumulation in the Curonian Lagoon was around the mouths of the Atmata and the Vytinė channels. In the second part of 20$^{th}$ century the accumulation of sediments in these areas decreased considerably, however an increase in sedimentation was observed in the mouth of the Skirvytė Tiesioji.

## DISCUSSION

According to the climate change forecast in the 21$^{st}$ century it is anticipated that due to rising sea level deltas with elevation below 2 m above sea level will be inundated over half of their land area (Ericson *et al.* 2006; Overeem, Syvitski 2009). The surface of the Nemunas delta is flat and low—most of it is not higher than 1.0–1.5 m—and the delta front is only 0.3–0.5 m above sea level. Significant parts of the delta front are lower than the average of the Baltic Sea level (up to –0.5 m). The lowest place in Lithuania is in the Nemunas delta, at the Dumblys Lake (1.3 m below sea level) (see Fig. 1). Even taking into account the most optimistic scenario of global sea level rise, inundation in the Nemunas delta is possible in the near future.

Such threats are increasing due to some peculiarities of the regional settings as discussed below. A summary of all the changes of land in the northern part of the Nemunas delta front for the period 1910–2005 (Table 7) indicates that during the last 47 years the annual increase of land area by sedimentation has diminished by 2.1 times.

This phenomenon was influenced by the significant decrease in the Nemunas River runoff during the second part of the 20$^{th}$ century (Fig. 4), which was caused by both natural and human factors. In 1959 when the Kaunas hydropower dam and station was constructed, a regulation of the Nemunas runoff was implemented. During winter season part of the water were released from the Nemunas dam in order to avoid any damage to the hydropower station during spring flooding. Due to the operations of the Kaunas hydropower station the annual decrease in runoff during floods is on average 7.8%, and in the case of small floods it reaches a 13% per year (Gailiušis *et al.* 2001).

In addition, by the end of the 20$^{th}$ century there were some 60 years of intensive construction of dams within the whole Nemunas River catchment. At present in Lithuania there are 434 dams, each with an area greater than 5 ha (Gailiušis *et al.* 2001). The Nemunas runoff has therefore decreased due to the water accumulated in these dams during the spring floods. The Neris River is the biggest tributary of the Nemunas (its length is – 509.5 km). In 1976, in the upper catchment of the Neris in Belarus territory, the Vileika–Minsk water system was established in order to improve water supply for the city of Minsk. This resulted in a dam being constructed on the Neris River at the township of Vileika, and water from the dam was pumped (10 % of water amount) to the Svisloc River in the Dniepr catchment (Gailiušis *et al.* 2001). The result of the construction of dams in the Nemunas catchment and water pumping to the Dniepr catchment from the Neris River resulted in the decre-

**Table 7** Changes of land area in the Nemunas delta front in the period 1910–2005. Compiled by D. Pupienis, 2012.

| Variation of delta front | 1910–1958 | | 1958–2005 | | 1910–2005 | |
|---|---|---|---|---|---|---|
| | Total, km$^2$ | Annual, km$^2$/year | Total, km$^2$ | Annual, km$^2$/year | Total, km$^2$ | Annual, km$^2$/year |
| Increase of land area | 8.37 | 0.17 | 4.20 | 0.09 | 12.57 | 0.13 |
| Erosion of land area | 1.44 | 0.03 | 1.05 | 0.02 | 2.49 | 0.02 |
| Total change of land area | 6.93 | 0.14 | 3.15 | 0.07 | 10.08 | 0.11 |

ase of annual runoff of the Nemunas in its lower catchment and during spring floods. The inflow to the Curonian Lagoon decreased by up to 18% (Gailiušis, Kriaučiūnienė 1998).

Therefore, with the construction of the Kaunas hydropower station the runoff from the Nemunas River during the spring flood has been reduced by 26–31% over the last 50 years. These changes in the Nemunas catchment also directly influence the amount of sediment material being transported to the Nemunas delta (Vaikasas 2009). A particularly large decrease in sediment transport at Smalininkai was observed by comparison with the annual average content of particles for the periods 1945–1960 and 1961–1996. The amount decreased from 680 000 to 356 000 tonnes per year (Žilinskas, Jarmalavičius 2001). Also, it was detected that the largest amount of sediment (about 58% of annual amount of drift matter) is transported during the spring floods (March–April), and this period also is marked by the greatest decrease in Nemunas runoff. The study showed that only about 7–11% of all particles transported by the Nemunas are reaching the Baltic Sea through the Klaipėda strait (Vaikasas, Rimkus 2003).

Sedimentation decrease in deltas due to human activities in river catchments (mainly due to dam construction) is a characteristic phenomenon throughout the whole world (Vörösmarty *et al.* 2003). It is estimated that 45 000 water dams in the world retain approximately 25–30% of sediments (Vörösmarty *et al.* 1997) that, under natural conditions, would be deposited in deltas. For instance, since 1950 sedimentation in the Yellow River delta has decreased by up to 90% (Ren, Walker 1998; Wang *et al.* 2007). Syvitski *et al.* (2005) estimated that on a

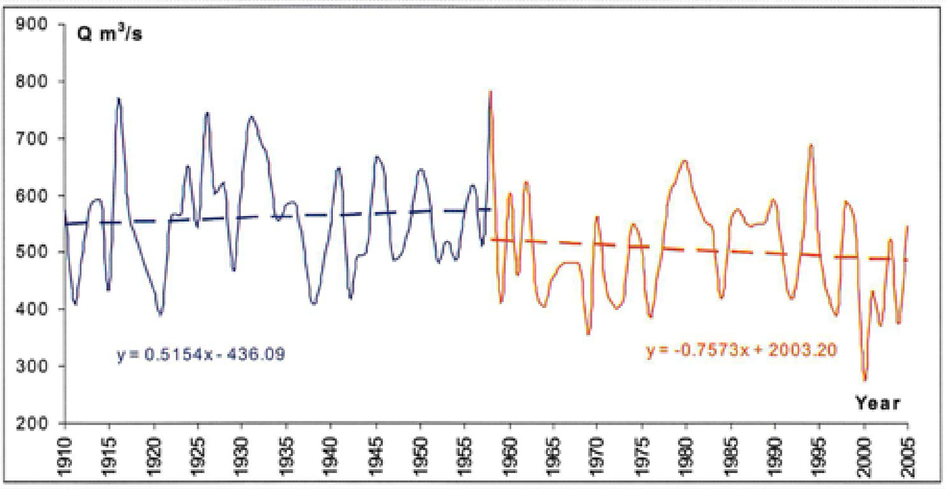


**Fig. 4** Mean Nemunas River runoff changes (and its trends) measured at Smalininkai. Blue solid line – Nemunas River runoff in the period 1910–1958, red solid line – Nemunas River runoff in the period 1958–2005. Compiled by D. Jarmalavičius, 2012.

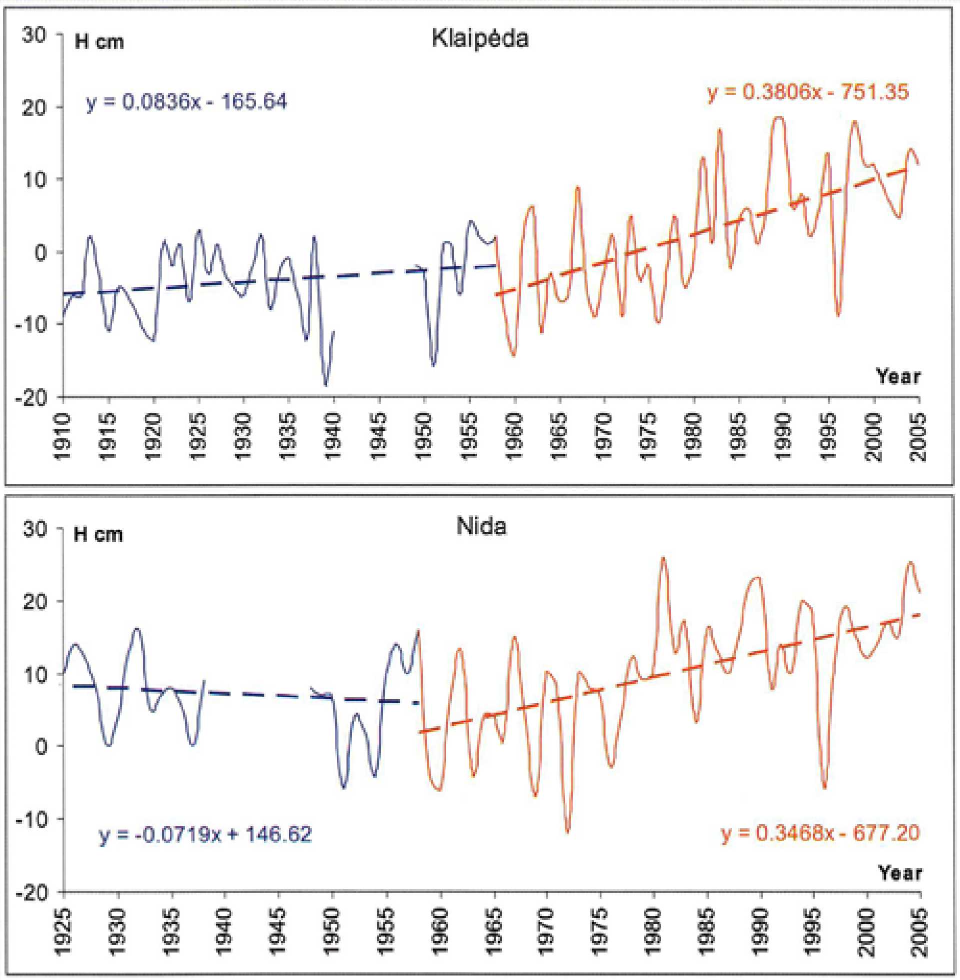


**Fig. 5** Mean annual sea level changes (and its trends) measured at Klaipėda (1910–2005) and Nida (1925–2005). Blue solid line – sea level changes in the period 1910–1958, red solid line – sea level changes in the period 1958–2005. Compiled by D. Jarmalavičius, 2012.

global scale 26% of the sediment that would flow to the coast and deltas has been intercepted by retention in reservoirs.

On the other hand, runoff from the Nemunas River also decreases due to climate change. During recent decades the years with lower precipitation and dry summers (Pankauskas, Bukantis 2006) are more frequent and snowy winters are more rare (Gečaitė, Rimkus 2010). During the period 1910–1958 the Nemunas annual mean runoff was 560.7 $m^3/s$, with trends of a slight increase of 0.52 $m^3/s$ ($p$=0.81). However, in the period 1958–2005 a different situation was observed and the mean annual runoff was 500.2 $m^3/s$ with decreasing trends by an average of 0.76 $m^3/s$ ($p$=0.83) (Fig. 4). Multiannual change of the Nemunas runoff has a cyclic variation (Gailiušis *et al.* 2011), therefore linear trends of the Nemunas runoff are negligible. According to various climate change scenarios the Nemunas runoff in the 21st century will decrease from 17 to 41% (Kriaučiūnienė *et al.* 2008).

The global ocean level rises at ≈1.8 to 3 mm/year (Bindoff *et al.* 2007), much higher rising of sea level is in the Curonian Lagoon, so it is another unfavourable circumstance for the Nemunas delta front. The analysis of water level dynamics at Klaipėda (Fig. 5) shows that during 1910–1958 the mean sea level was on the rise +3.5 cm, and the trend of its rise was only +0.8 mm/year ($p$=0.08). But during 1958–2005 the mean annual water level increased to +3.0 cm, and the trend of its rise increased up to +3.8 mm/year ($p$=0.00). The water level change at Nida during 1925–1958 has reverse trend –0.7 mm/year ($p$=0.59), and during the next period 1958–2005 the water level trend was positive and increase up to +3.5 mm/year ($p$=0.00) (Fig. 5). Klaipėda and Nida's water level linear trends in the first period are negligible due to discontinuity in data series, but in the second period the trends are significant. The water level rise in Curonian Lagoon has the same tendency as global ocean water level rise (Bindoff *et al.* 2007). Since the Curonian Lagoon is connected to the Baltic Sea the level of the lagoon is changing respectively. Although the lagoon water level is often higher than in the Baltic Sea—especially in spring time due to the Nemunas water inflow—the rising sea level causes an increasing damming effect on the water of the Nemunas delta.

One more unfavourable circumstance for the Nemunas delta front development is neotectonic subsidence. According to recent data (Zakarevičius *et al.* 2009) the land in the delta region is subsiding at a rate of 2.5 mm per year. Thus, if the effects of neotectonic land subsidence and lagoon level increase (about +3 mm/year) are added together then hypothetically it would imply that during the next few years the largest part of the Nemunas delta front will be inundated, because the main part of its surface is not higher than 0.3–0.5 m above the current water level, and a considerable part is below sea level. Inundation also will be facilitated by a decrease in the volume of particulates' sedimentation.

## CONCLUSION

Intensive decrease in Nemunas River runoff and transport of sediment has been observed since the middle of the 20th century due to anthropogenic activity (construction of hydropower stations, dams, and the pumping of water from the Nemunas catchment to the Dnieper catchment, and natural factors (water volume decrease in the Nemunas and its tributaries). At the same time a rise in the water level in the Baltic Sea and the Curonian Lagoon, as well as land subsidence in Nemunas delta region have been observed. Due to these factors sediment accumulation is diminishing in the Nemunas delta front. As a consequence the land area in the northern part of the Nemunas delta front decreased more than 2.1 times in the period 1958–2005, in comparison with the land area measured in the period 1910–1958. If the observed trend continues in the future, sediment accumulation will be replaced by erosion in the delta front during the next few years.


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