Environ Earth Sci
DOI 10.1007/s12665-011-1152-3

ORIGINAL ARTICLE

Dynamics of beaches of the Lithuanian coast (the Baltic Sea) for the period 1993–2008 based on morphometric indicators

Darius Jarmalavičius · Jonas Satkūnas · Gintautas Žilinskas · Donatas Pupienis

Received: 19 February 2010 / Accepted: 11 June 2011

Abstract The investigations were carried out in order to evaluate change of the beaches profile during the period 1993–2008 and to elucidate main trends of the coastal dynamics. Morphometric indicators (beach width, height and inclination) were measured every year during the period 1993–2008 in 70 measuring stations located along the coastline. It was determined that the dynamic shoreline of the mainland during 1993–2008 receded by 10.2 m and the dynamic shoreline of the Curonian Spit advanced into the sea by 8.3 m. The different morphometric beach indicators changed to varying extents over the period 1993–2008, but comparison of values for 1993 and 2008 showed that those changes were small. The average beach width increased by 1.2 m on the mainland coast and by 0.5 m on the Curonian Spit coast. The average beach height also increased negligibly: by 0.5 m on the mainland coast and by 0.1 m on the Curonian Spit coast. The average beach slope inclination increased by 0.012 (from 0.065 to 0.077) on the mainland coast and by 0.005 (from 0.073 to 0.078) on the Curonian Spit coast. The measurements show that, despite being the most dynamic elements in the coastal system, these beaches managed to retain their morphometric indicators almost unchanged during the period of observation.

Keywords The Baltic Sea · Curonian Spit · Beach · Coastal dynamics · Beach morphometric indicators

D. Jarmalavičius · G. Žilinskas · D. Pupienis
Institute of Geology and Geography,
Ševčenkos 13, LT-03223 Vilnius, Lithuania

J. Satkūnas (✉)
Vilnius University, Čiurlionio 21,
LT-03123 Vilnius, Lithuanian
e-mail: jonas.satkunas@lgt.lt

J. Satkūnas
Geological Survey, Konarskio 35,
LT-03123 Vilnius, Lithuanian

G. Žilinskas
Institute of Maritime and Cultural Landscapes,
Klaipėda University, H. Manto 84,
LT-92294 Klaipėda, Lithuania

Introduction

Changes of coastlines and beaches have significant economic and social impacts on human populations concentrated in coastal areas. Beaches in particular play an important role for coastal protection and recreation.

Coastal change is a complex result of an interaction of climate driven eustatic sea level change, vertical crustal movements, hydrodynamic and aeolian processes and human interactions. Coastal change may be a relatively slow or very rapid process. Often, during storms, beach morphology can change substantially in a few, hours. Hydrodynamic and aeolian processes in the beach act as the main driving forces of sand movement along and across the shore (dune ridge–sea–beach–dune ridge) changing not only the morphometric characteristics of the beach but also the composition of beach sediments.

The reconstruction of changes in coastal morphometric parameters in the past as well as the examination of present processes indicate that during transgression and regression the shore components experience constant transformation, often of cyclical pattern (Bristow and Pucillo 2006; Costas et al. 2006; Hine 1979; Tamura et al. 2008; Thom and Hall 1991). The most sensitive element of sandy coast, directly experiencing the impact of waves,

Published online: 29 June 2011

is the beach. Therefore, the changes in beach profile reflect the changes in dominating factors, among which the main are wave energy and the composition of coastal deposits (Hsu and Wang 1997; Musielak 1989; Pena and Lanfredi 1988; Shibayama and Horikawa 1985; Short and Hesp 1982; Swain and Houston 1984; Türker and Kabdasli 2006). Examining the dependence of changes in beach profile on the dominating factors the relationship between the foreshore slope and the mean grain size is most often analysed (Dubois 1972; McLean and Kirk 1969; Swart 1991). It was determined that coarser the sand forming the beach, the steeper the shore. However, this relationship will vary for shores with different wave energies. The beach profile will be flatter in the coasts with higher wave energy comparing with the coasts of the same sand composition but affected by lower wave energy (Bascom 1951; Wiegel 1964).

Substantial attention is paid to the geological and geomorphological research on southeastern Baltic shores (Fig. 1). Since the morphometric and geological features of this region's shores are quite similar (shallow and sandy beaches), results from neighbouring countries are important when analysing the features of Lithuanian shoreline dynamics and comparing these with the specific details of dynamics in neighbouring countries. In Poland, the dynamics of beach morphometry have been analysed in a short coastal sector near Liubiatowo (Zawadzka 1989; Pruszak et al. 2008). In the Kaliningrad Region (Russia), research is being undertaken on the mainland shore and the Vistula and Curonian Spits. The research is based on previous work undertaken by German researchers as well as recent observations (Boldirev 1998; Bobykina and Boldirev 2008; Burnashov and Scherbina 2008). Following the publication of new monitoring data and analysis of cartographical material in relation to shoreline dynamics in Latvia (Eberhards et al. 2009) active research has been undertaken there.

In Lithuania, the short-term or seasonal dynamics of beach morphology have been analysed for short coastal sectors: stationary polygons investigated in Nida (Kirlys 1967; Kirlys and Stauskaitė 1979, 1981; Kirlys et al. 1981; Karaliūnas 1987), Būtingė (Žilinskas 1994), the impact zone of Klaipėda port (Žilinskas and Jarmalavičius 2000), and Palanga (Žilinskas et al. 2008; 2010). The characteristics of the beaches of the entire Lithuanian coast (measured every 500 m) have been discussed (Žilinskas and Jarmalavičius 1997) but only certain aspects of their short-term (after hurricanes) and long-term dynamics have been touched upon in a number of articles (Jarmalavičius and Žilinskas 2001, 2002; Žilinskas et al. 2000, 2005; Žilinskas and Jarmalavičius 2003; Žilinskas 2005).

The studies of the Lithuanian coasts during the last 25 years have indicated that the coastal sectors dominated by accretion and erosion processes have been revealed (Žilinskas 2005; Žilinskas and Jarmalavičius 2003). However, wave energy indices and composition of coastal deposits remain practically unchanged during the research period (Žilinskas et al. 2001). The main objective of this paper is to determine dynamics of the beach profiles in the coastal sectors dominated by accretion and erosion processes taking into consideration that wave energy indices and composition of coasts remain unchanged.

Study area

The Baltic Sea is geologically very young: the development of the present Baltic Sea started after the retreat of the glaciers of the last Late Weichselian glaciation, i.e. 13,000 years BP (Gudelis and Kőnigsson 1979). Glacial meltwater filled the Baltic Sea depression and a large Baltic ice lake appeared which later merged with the Atlantic Ocean. This lake existed between 13,000 and 10,000 years ago. During the next few stages of the Baltic Sea development—the Yoldia Sea and Ancylus Lake—water level was significantly lower than at present (Povilanskas et al. 2009). The main period of the Lithuanian seacoast formation was the second Littorina Sea (Post-Littorina) transgression, when the water level was a few metres higher than at present (Gudelis 1998). At the end of the Littorina stage (4,000–4,500 BP) isostatic uplift caused regression of the Littorina Sea. Gradually, the coastline of the Baltic Sea attained its present position. However, the present physiographic shape of the Lithuanian coast was formed only at beginning of the first millennium AD (Gudelis 1998).

The length of the Lithuanian Baltic Sea coast is only 90.6 km (Žilinskas 1997): 51.03 km on the Curonian Spit and 38.49 km on the mainland. These are separated by the 1.08 km wide Klaipėda strait (Fig. 1).

The Lithuanian coast is formed exclusively of Quaternary deposits. According to the Geological Atlas of the Lithuanian Coast of the Baltic Sea (Bitinas et al. 2005), the continental coast and the coast of the Curonian Spit are very different geologically and geomorphologically. Glacial (moraine) deposits formed during last glaciation are characteristic for the central part of continental coast and in most cases are exposed in the cliffs. The sandy sediments that were formed mainly in the Littorina and Post-Littorina Seas and their lagoons prevail in coastal structure in the northern (Šventoji, Palanga) and the southern parts of the continental coast (Giruliai, Melnragė).

The upper part of the Quaternary deposits in the Curonian Spit is composed of sediments that have formed in the basins of the various stages of the Baltic Sea's development—starting from the Baltic Ice Lake and ending with

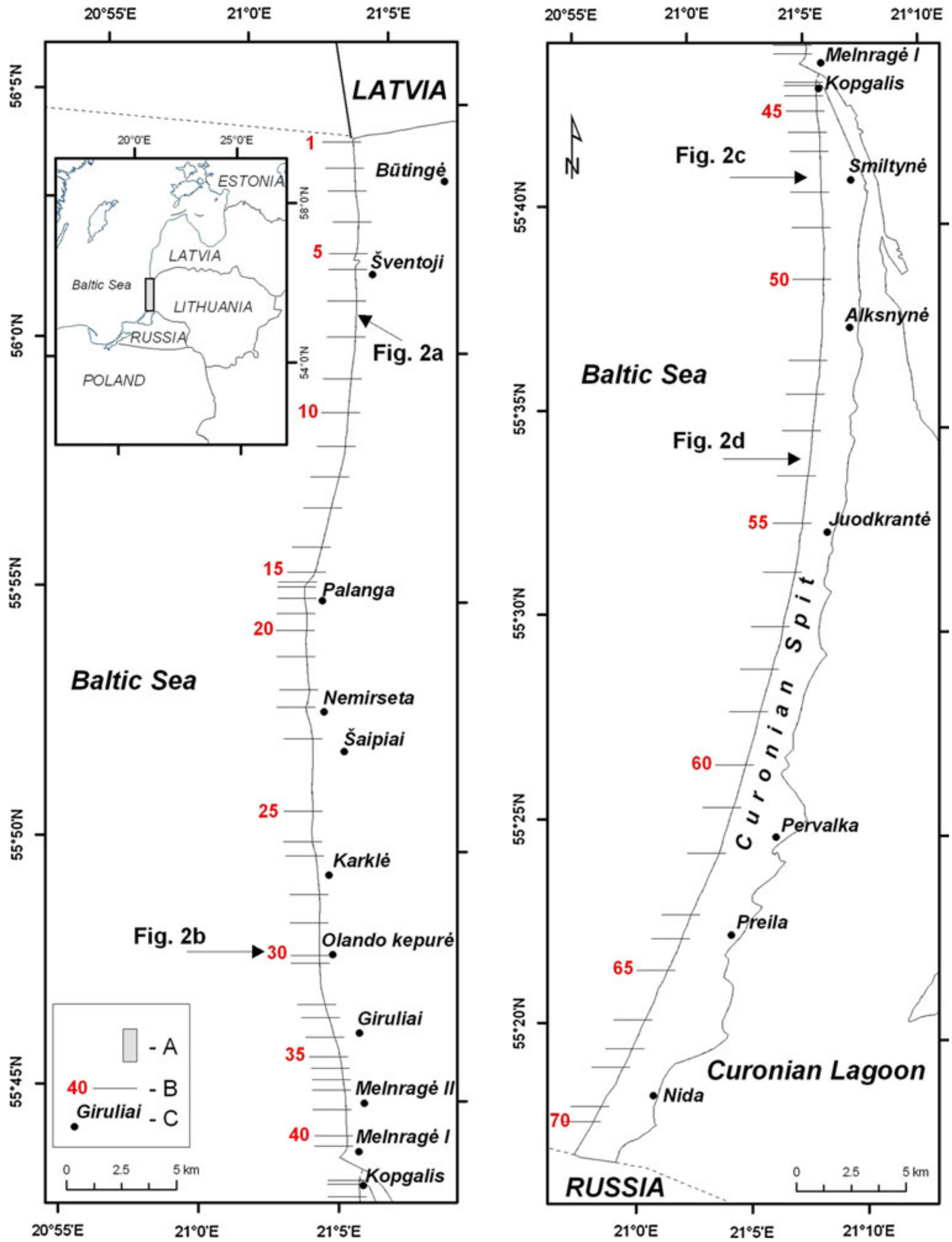

Fig. 1 Location of the study area. **a** Study area, **b** Profile location and its number, **c** Locality

recent marine sediments (Bitinas et al. 2005). Glacial deposits in the Curonian Spit are found only at depths of 25–30 m below the present sea level.

Along entire coast of the Curonian Spit the beaches are bordered on the east side by artificial foredunes. The mainland coast is geomorphologically more diverse: beach foredunes occupy 28.1 km, or 74.4% of the coastline; morainic and sand cliffs occupy 5.62 km, or 14.9%; and coastal dunes 3.73 km, or 9.87% of the continental coastline.

Sandy sediments dominate in the composition of the surficial formations of the sea beaches. According to generalised data (Žilinskas et al. 2001), some 51.5% of coastal surficial formations consists of fine-grained sand; 37.8%, medium-grained sand; 8.8%, coarse-grained sand and 1.9% by gravel. Fine-grained sand forms the beaches of Šventoji, Palanga, Kopgalis, Smiltynė and Alksnynė (Fig. 2c). Medium-grained sand forms beaches between Šventoji and Palanga, beaches of Nemirseta, Giruliai and Nida (Fig. 2a). Coarse-grained sand dominates in the Ist and IInd beaches of Melnragė and in Juodkrantė (Fig. 2d). The surfaces of separate coastal courses (Būtingė, Šaipiai, Pervalka, Preila) are formed by sand with 5–30% gravel. Gravel, cobble and boulders cover up to 70–90% of the beach surface at Karklė and Olandų Kepurė (Fig. 2b). Given that the Baltic Sea is non-tidal, wind-generated waves are the main beach-forming factor.

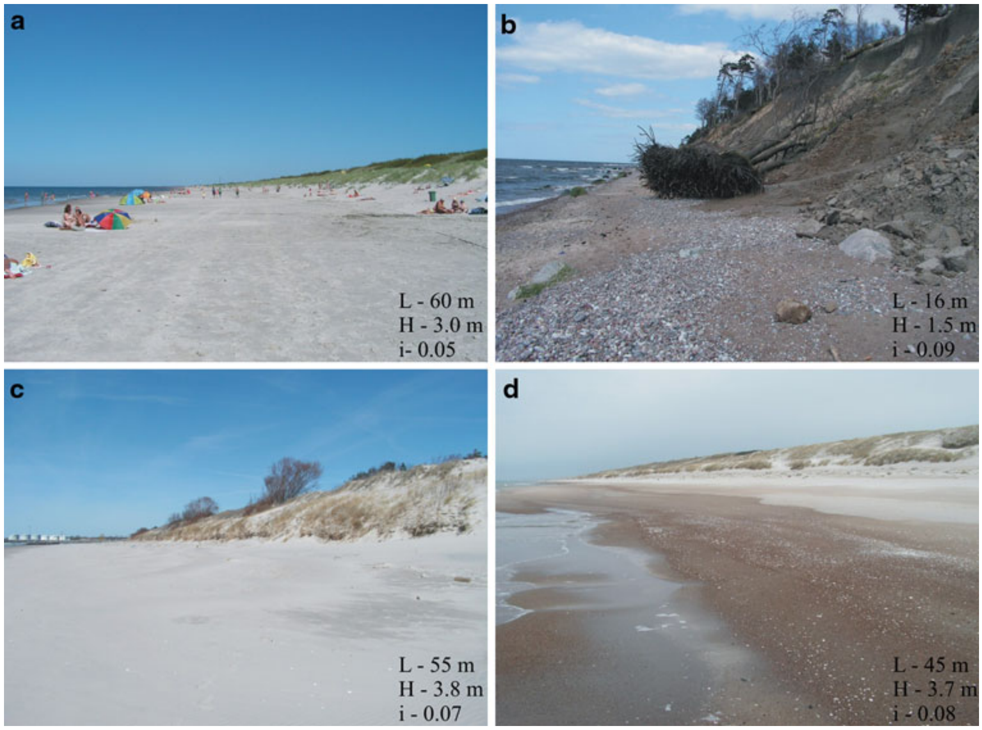

Fig. 2 Examples of morpho-lithological types of coast **a** Coast south of Šventoji, **b** Coast at cliff Olando Kepurė, **c** Coast at Kopgalis, **d** Coast of Juodkrantė (for symbols explanation see Fig. 3)

Methods

In order to evaluate the change of beach profile in sectors dominated by different dynamic processes, accretion and erosion, the changes of beach morphometric parameters that occurred during the last 15 years were analysed. The levelling of cross-profiles of the coast was performed (using electronic tachometer TOPCON GTS 229) in 70 measuring stations installed along the Lithuanian coast in 1993 (29 on the Curonian Spit and 41 on the mainland coast; from the border with Latvia to that with Russia) (Fig. 1).

The following morphometric indicators were chosen for analysis of morphological changes of the beaches: beach width (distance between the shoreline and the dune ridge foot), beach height (difference between the altitude of beach surface at the dune ridge foot and its altitude at the shoreline in view of the average long-term Baltic Sea level) and inclination (ratio between the beach height and width) (Fig. 3). These parameters were selected as being the best to represent the features of beach profile. Their description is presented by Žilinskas and Jarmalavičius (1997). The obtained field data served as a basis for interpretation and evaluation of the shoreline dynamics in 1993–2008. In order to eliminate local changes, resulting from the rhythmic topography and rip cells, the beach profile data were averaged for the mainland and Curonian Spit coast separately.

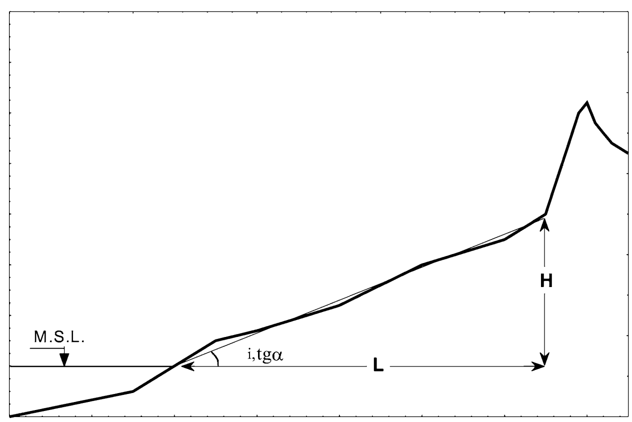

Fig. 3 Morphometric indicators of the beach: beach width (L), beach height (H), beach inclination (i, tgα). M.S.L.—mean sea level (after Žilinskas and Jarmalavičius 1997)

Results

Dynamics of beach width

Analysis of the statistical indicators of the beach width during the time span under consideration (Table 1) showed that in 1993, the average beach width on the mainland coast was 42.5 m and on the Curonian Spit it was 50.3 m. The mainland beach of the Olando Kepurė morainic cliff and the Curonian Spit beach at Juodkrantė settlement had

Table 1 Statistical characteristic of beach width in 1993–2008 years

	Mainland coast			Curonian Spit coast		
	1993	2002	2008	1993	2002	2008
Mean, m	42.5	51.2	43.7	50.3	49.0	50.8
Min, m	21.0	16.0	11.0	33.0	38.0	26.0
Max, m	76.0	137.0	107.0	71.0	69.0	85.0
Standard deviation	12.0	21.9	17.6	10.7	7.94	10.1

the smallest widths: 21.0 and 33.0 m, respectively. The widest beaches were measured at the mainland Palanga sector (76.0 m) and Kopgalis sector of the Curonian Spit (71.0 m) (Table 1). It should be noted that in the bays formed by stronger storms, the beaches may narrow to only a few metres and in the promontories they may widen to as much as 100 m. However, these extreme transformations are usually temporary and in a few months, the beach width almost returns to its original size.

In order to illustrate transitional values, the measurements for the year 2002 are shown in Figs. 4, 5 and Table 1. In 2002, the mean beach width of the continental coast was 51.2 m, and that of the Curonian Spit, 49.0 m. The narrowest beaches were at Karklė (mainland coast)—width 16.0 m—and 38.0 m close to Pervalka on the Curonian Spit. The widest beaches were measured at Šventoji (mainland coast)—137.0 m—and 69.0 m wide at Smiltynė II on the Curonian Spit.

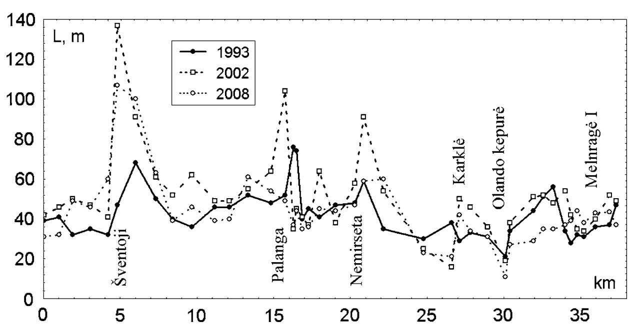

Fig. 4 Beach width distribution along the mainland coast in 1993–2008. Abscissa axis "0"—state border with Latvia

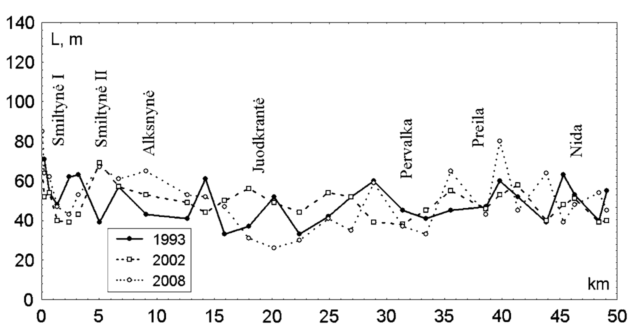

Fig. 5 Beach width distribution along the Curonian Spit coast in 1993–2008. Abscissa axis "0"—Klaipėda port jetty

In 2008, the average beach width on the mainland coast was 43.7 m and on the Curonian Spit was 50.8 m. The mainland beaches of the Olando Kepurė morainic cliff and the Curonian Spit beaches at Juodkrantė settlement were distinguished by the smallest widths: 11.0 and 26.0 m respectively. The widest beaches were characteristic of the mainland Šventoji sector (107.0 m) and Kopgalis sector of the Curonian Spit (85.0 m).

Analysis of beach width dynamics from 1993 to 2008 (Fig. 4) has shown considerable beach widening at the Šventoji settlement, north of Palanga, south of Nemirseta and at Melnragė II. Beaches have narrowed in the sector between Šventoji and Ošupis, at Palanga, and in the sector between Šaipiai and Giruliai. In the Curonian Spit (Fig. 5), beaches have widened at Smiltynė II, Alksnynė, south of Pervalka, at Preila and in the sector between Preila and Nida. Narrowing of beaches has been recorded at Smiltynė I, in the sector between Juodkrantė and Pervalka and north of Nida.

Dynamics of beach height

It has been determined (Table 2) that in 1993, the average heights of beaches were: 2.6 m on the mainland coast and 3.6 m on the Curonian Spit. The lowest beaches were characteristic of the mainland shore sector between Būtingė and Šventoji settlements (1.3 m) and the sector north of Juodkrantė on the Curonian Spit (2.5 m). The highest beaches were recorded in the Melnragė I sector of the mainland coast (3.8 m) and Juodkrantė sector on the Curonian Spit (4.5 m).

In 2002 the mean beach height was 2.9 m on the mainland coast and 3.2 m on the Curonian Spit. The lowest beaches were at Palanga (1.4 m) on the mainland and 2.1 m at Smiltynė I (Curonian Spit). The highest beaches–6.0 m—were measured at Šventoji (mainland) and 4.1 m at Juodkrantė (Curonian Spit).

In 2008, the average heights of beaches were: 3.1 m on the mainland coast and 3.7 m on the Curonian Spit (Table 2). The lowest beaches were characteristic of the mainland coastal sector at Olando Kepurė cliff (1.6 m) and

Table 2 Statistical characteristic of beach height in 1993–2008 years

	Mainland coast			Curonian Spit coast		
	1993	2002	2008	1993	2002	2008
Mean, m	2.6	2.9	3.1	3.6	3.2	3.7
Min, m	1.3	1.4	1.6	2.5	2.1	2.6
Max, m	3.8	6.0	5.3	4.5	4.1	4.4
Standard deviation	0.7	0.9	1.0	4.5	0.6	4.4

the coastal sector at Preila on the Curonian Spit (2.6 m). The highest beaches were characteristic of the Šventoji coastal sector of the mainland coast (5.3 m) and beaches south of Juodkrantė on the Curonian Spit (4.4 m).

The greatest changes of beach height in the period 1993–2008 (Figs. 6, 7) occurred in the sector of mainland coast between Būtingė and northern part of Palanga. At Šventoji, the beach height locally doubled. Increased beach height was also observed at Nemirseta and Melnragė I and II. On the Curonian Spit, beach height varied by smaller amounts. It increased in the coastal sectors at Alksnynė, south of Juodkrantė and at Preila and Nida.

A tendency towards beach lowering has been observed on the mainland coast at Palanga, the coastal sector of the Šaipiai–Karklė morainic massif and at Giruliai. Reduction of the heights of beaches on the Curonian Spit has been

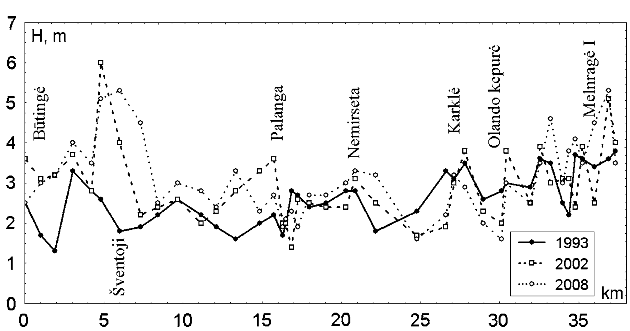

Fig. 6 Beach height distribution along the mainland coast in 1993–2008. Abscissa axis "0"—state border with Latvia

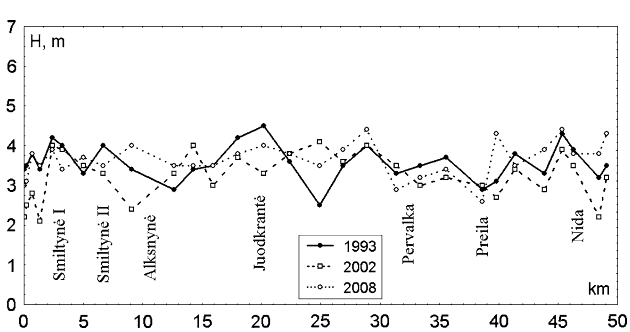

Fig. 7 Beach height distribution along the Curonian Spit coast in 1993–2008. Abscissa axis "0"—Klaipėda port jetty

recorded at Kopgalis, Smiltynė I and II, Juodkrantė and in the Pervalka–Preila sector.

Dynamics of beach inclination

Though this morphometric indicator is a derivative of the width and height values of the beach, it is characterised by the highest temporal stability. Because of the number of accidental factors such as rhythmic topography and rip cells the correlation of beach width between 1993 and 2008 was weak ($r = 0.39$ in mainland coast and $r = 0.37$ in Curonian Spit coast). Correlation of the beach height between 1993 and 2008 was also estimated as weak ($r = 0.26$ in mainland coast and $r = 0.38$ in Curonian Spit coast). However, rather good correlation $r = 0.66$ (mainland coast) and $r = 0.50$ (Curonian Spit coast) of beach inclination between 1993 and 2008 was received. This implies that beach inclination is best morphometric indicator of the long-term tendencies of beach dynamics.

Analysis of statistical indicators of beach slope inclination in 1993 (Table 3) has shown that the average slope inclination of the mainland beach was 0.065 and of then Curonian Spit beach was 0.073. The smallest inclination was observed at Palanga on the mainland coast (0.022) and at Kopgalis on the Curonian Spit (0.047). The greatest inclination was observed at the mainland beaches of Olando Kepurė morainic massif (0.127) and at Juodkrantė in the Curonian Spit (0.114).

In 2002, the average beach inclination of continental coast was 0.063, and of the Curonian Spit was 0.068. The smallest inclinations (0.034) were found at both Palanga (mainland) and Kopgalis (Curonian Spit). The greatest inclination (0.119) was at Karklė beach (mainland) and 0.103 north of Pervalka on the Curonian Spit.

In 2008, the average slope inclination of the mainland beach was 0.077 and of the Curonian Spit beach 0.078. The smallest inclinations have been recorded at Palanga on the mainland coast (0.043) and at Kopgalis on the Curonian Spit (0.035). The steepest inclinations were observed at the mainland beaches of the Olando Kepurė morainic massif (0.145) and at Juodkrantė on the Curonian Spit (0.154).

Analysis of the dynamic patterns of beach slope inclination between 1993 and 2008 (Figs. 8, 9) has shown that the greatest increase occurred in the mainland coast sector

Table 3 Statistical characteristic of beach inclination in 1993–2008 years

	Mainland coast			Curonian Spit coast		
	1993	2002	2008	1993	2002	2008
Mean, m	0.065	0.063	0.077	0.073	0.068	0.078
Min, m	0.022	0.034	0.043	0.047	0.034	0.035
Max, m	0.127	0.119	0.145	0.114	0.103	0.154
Standard deviation	0.02	0.022	0.02	0.02	0.017	0.03

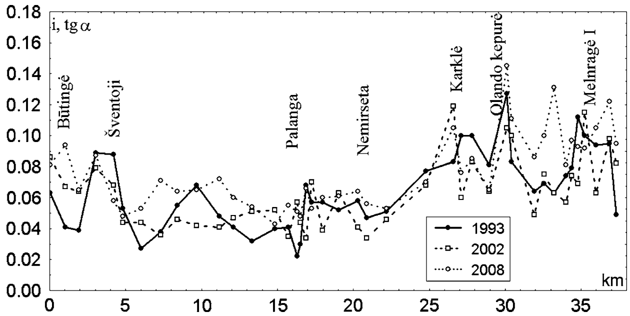

Fig. 8 Beach inclination distribution along the mainland coast in 1993–2008. Abscissa axis "0"—state border with Latvia

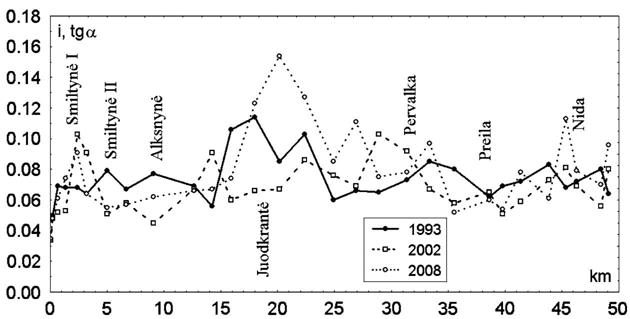

Fig. 9 Beach inclination distribution along the Curonian Spit coast in 1993–2008. Abscissa axis "0"—Klaipėda port jetty

between Būtingė and Palanga, at Nemirseta and between Giruliai and Melnragė I. In the Curonian Spit, the beach slope inclination increased at Smiltynė I, between Juodkrantė and Pervalka and at Nida. Tendencies towards reductions of beach slope inclination have been observed at Karklė and Melnragė in the mainland sectors and between Smiltynė II and at Alksnynė and between Pervalka and Preila on the Curonian Spit.

Generalising the distribution patterns of morphometric beach indicators in 1993–2008 (Tables 1, 2, 3) we may state that they were little changed. The average beach width increased by 1.2 m on the mainland coast and by 0.5 m on the Curonian Spit coast. The average beach height also increased negligibly: by 0.5 m on the mainland coast and by 0.1 m on the Curonian Spit oast. The average beach slope inclination increased only slightly: by 0.012 (from 0.065 to 0.077) on the mainland coast and by 0.005 (from 0.073 to 0.078) on the Curonian Spit coast.

The presented data show that the morphometric indicators of beaches along the Lithuanian coast, in general, have remained essentially unchanged apart from some small changes on the coast of the Curonian Spit. Somewhat more distinctive changes have been recorded in the beaches of the mainland coast characterised by more variable sediment composition and greater anthropogenic impacts.

However, analysis of dynamic patterns of morphometric indicators of beaches in different coastal sectors (Figs. 4, 5, 6, 7, 8, 9) has shown more significant changes. In most coastal sectors, the width, height and inclination of beaches have increased. The most intensive sediment accumulation has taken place in the Šventoji sector of the mainland coast where beaches have widened and heightened, yet the slope angle of the beach has remained almost unchanged. The width and height of the beach has also increased north of Palanga. However, in this sector, the marked increase of the height has occurred with simultaneous increase of the slope inclination: the beach has become slightly steeper. In the coastal sector south of the Palanga pier, beaches have narrowed and lowered whereas the slope inclination has remained unchanged. In the sector between Palanga and Giruliai, the changes of morphometric indicators of the beach were not marked. The beach has narrowed at Giruliai whereas it has widened, heightened and become steeper at Melnragė II. A reduction of beach width and height has been recorded north of the Klaipėda port jetties.

During the time span under consideration, beaches also have lowered and flattened in the southern part of the Curonian Spit: Kopgalis and Smiltynė. In the coastal sector of Smiltynė II–Alksnynė, beaches have been widening and heightening yet getting flatter. In the central part of the Curonian Spit, at Juodkrantė, beaches have been narrowing and lowering yet getting steeper. Similar transformation patterns have been characteristic in the sector at Pervalka. South of Pervalka to the state border with Russia, tendencies of distribution dynamics of morphometric indicators along the coast have not yet been fully determined but in short coastal sectors, morphometric indicators increase or reduce, alternately.

Generalising, it can be stated that in the period under consideration (1993–2008) while morphometric indicators of beaches have changed considerably in some individual coastal sectors their average values on the Lithuanian coast have changed negligibly.

Discussion

When analysing the dynamics of morphometric indicators of beaches it is necessary to bear in mind changes of the shoreline that have taken place in 1993–2008. It should be noted that the coast is relatively stable where beach width reaches some 40 m (Zawadzka 1989; Pruszak et al. 2008). Comparison of the changes of the shoreline and beach width that have taken place in the 15 years from 1993 to 2008, shows that the dynamic shoreline receded by 10.2 m on the average whereas the average beach width slightly increased (+1.2 m). Previous studies have shown that regression of the shoreline influences active erosion of the dune ridge, i.e. the dune ridge regresses together with the shoreline (Žilinskas et al. 2000, 2005). As a result, the beach width remains quasi-stable. It should be emphasised that temporal quasi-stability can be proved only by analysis of the changes of average beach width along the whole mainland coast. Meanwhile, in some coastal sectors, these changes were more marked. Beach width in different sectors of the mainland coast ranged from −39 to +60 m and the shoreline from −68 to +20 m (Table 4).

In 1993–2008, the shoreline of the Curonian Spit advanced into the sea by 8.3 m on the average, whereas the beach widened only by 0.5 m, i.e. the average width of the spit beaches remained almost unchanged. Yet, unlike the mainland coast, the stability of beach width of the Curonian Spit was predetermined by the advance of the western slope of the dune ridge towards the sea (as a result of sediment accumulation at the dune ridge foot). In some sectors of the Curonian Spit coast, the beach width ranged from −26 to +28 m and the shoreline from −18.5 to +49 m (Table 4).

A wide range of variation of beach width over a short timescale was observed in a narrow 2.5 km long coastal segment of the Polish Baltic Sea coast (Pruszak et al. 2008). Those changes took place due to variable of dislocation of small bays and capes along the shore. Analysis of long-term changes of beach width averaged for each coastal segment, instead of individual profile, avoids such temporary fluctuations due to rhythmic topography. Thus, it could be seen that the range of average width of the beach changed only marginally. Similar patterns have been observed also on Latvia's coast. The dynamics of the Latvian coast analysed by Eberhards et al. (2009) revealed changes across the shoreline from −150 to +70 m in 1935–1990 and from −50 to +30 m in 1992–2007 while the width of the beach did not experience large changes and remained rather stable.

When analysing the shoreline dynamics on the Curonian Spit, part of which belongs to Russia, it has been established that the shore in Southern part shrunk back 100 m in 70 years, and in the northern part, it advanced 200 m during the same time. Despite such an intense shift of the sea shoreline, the beach's width remained almost the same: in the southern part 25–33 m and the northern 60–90 m (Boldirev 1998).

Thus, the dominant shoreline regression on the mainland coast and transgression on the Curonian Spit coast have not significantly changed the average width of the beaches. Only in certain sectors were beach width variations rather marked. Short-term changes of the beach width can be illustrated by observations beach at Smiltynė (Fig. 10 pav.), where, over 16 years, the beach width changed between 43 m (in 1998) to 71 m (in 2006), and the amplitude of change of the beach was 28 m. However, in spite of considerable changes in individual years, the long-term average width of the beaches remained stabile.

Morphometric indicators of beaches on the mainland coast have almost not changed at the expense of erosion of the dune ridge, i.e. regression of the shoreline and narrowing and lowering of beaches contribute to stronger erosion of dune ridge. The dune ridge regression, in its turn, contributes to beach widening and heightening (Fig. 11).

On the coast of the Curonian Spit, where shoreline transgression is dominant, the morphometric indicators of beaches remain almost unchanged due to dune ridge accretion, i.e. transgression of the shoreline to the sea contributes to beach widening and heightening as well as to intensive sand accumulation at the dune ridge foot (Fig. 12).

A similar process when beach widening creates favourable conditions for the formation of the dune ridge nearer the coastline was observed by other researchers (Thom and Hall 1991). A similar quasi-stationarity of profile form was observed in other coastal morphometric elements, for example, examining the berm development

Table 4 Statistical characteristic of beach width and coastline dynamics in 1993–2008 years

	Beach width dynamics, m		Coastline dynamics, m	
	Mainland coast	Curonian spit coast	Mainland coast	Curonian spit coast
Mean, m	+1.2	+0.5	−10.2	+8.3
Min, m	−39.0	−26.0	−68.0	−18.5
Max, m	+60.0	+28.0	+20.0	+49.0

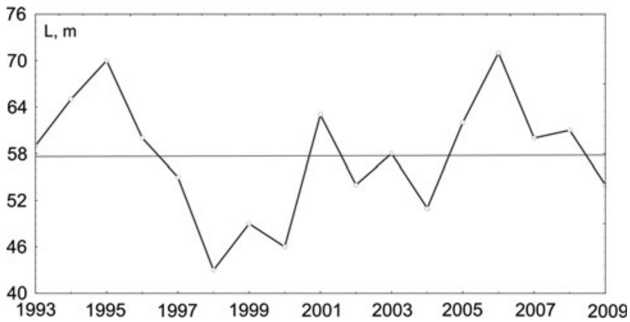

Fig. 10 Change of beach width along cross-profile No. 49 during 1993–2009

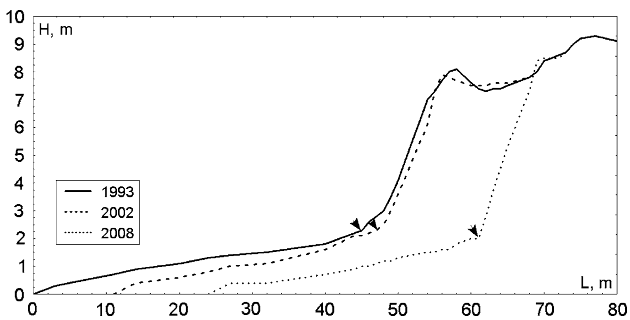

Fig. 11 Dynamics of coastal cross-section on erosion dominated coastal sector in 1993–2008 near the Palanga (profile No. 18). *Arrows* indicate position of dune ridge foot. $\Delta L = -7$ m, $\Delta H = -0.2$ m, $\Delta i = +0.004$, Δ shoreline $= -25$ m (for symbols explanation see Fig. 3)

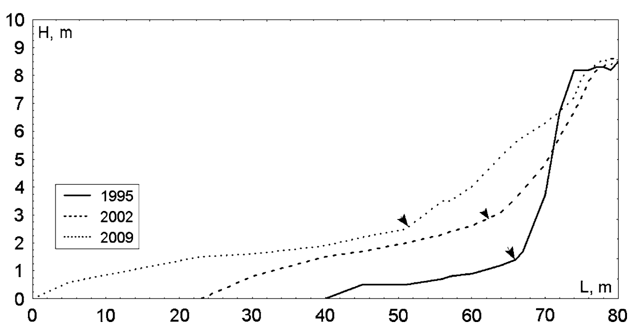

Fig. 12 Dynamics of coastal cross-section on accretion dominated coastal sector in 1995–2009 between Preila and Nida (profile No. 66). *Arrows* indicate position of dune ridge foot. $\Delta L = +26$ m, $\Delta H = +1.0$ m, $\Delta i = -0.004$, Δ shoreline $= +40$ m (for symbols explanation see Fig. 3)

mechanism it was noticed by Hine (1979) that berm development on transgressive shore is not gradual but a new form of similar profile is created.

Conclusions

A comparative analysis of morphometric indicators of beach dynamics in 1993–2008 has shown that, over the 15 years, their average values practically have not changed either on the mainland coast or on the coast of the Curonian Spit. Their temporal stability can be explained as follows.

In the coastal sectors with prevailing accretion processes the widening of beach produces the favourable conditions for wind transportation of larger sand masses (due to the increased sediment volume in a beach and wind fetch distance), and the formation of dune ridge closer to the shoreline. Due to the transgression of dune ridge, the beach morphometric indicators remain only slightly changed.

In the coastal sectors with prevailing erosion processes, the narrowing of beaches allows the waves to erode the dune ridge. The part of material from regressing dune ridge is accumulated at the beach, resulting in the recovery of beach profile. In such way, the beach profile retains quasi–stability in the coast dominated by accretion processes as well as in the coast with prevailing erosion processes. In essence, if the essential factors forming the beach—the wave energy and the composition of beach deposits—do not change, the beach profile tries to return into equilibrium with the forming factors.

The quasi–stability of beaches is revealed only by analysis of the average long-term measuring data over long coastal sectors (in this case, the Lithuanian mainland coast and the coast of Curonian Spit). Analysis of long-term dynamics of morphometric indicators of beaches in shorter coastal sectors or individual profile has shown that they may vary considerably due to rhythmic topography and rip cells. The greatest changes of morphometric indicators have been observed in those coastal sectors that have greater morpho-lithological diversity and anthropogenic loads. This is especially evident in the mainland coast. The measured morphometric indicators are of great value for planning coastal infrastructure and adaptation to climatic variations.

Acknowledgments The authors are grateful to Ms. Ada Jurkonytė for translation this manuscript into English and Dr. Brain Marker (UK) for kind checking of English translation. Thanks are extended to reviewers for valuable comments and remarks that served for improvement of the paper.

References

Bascom WH (1951) The relationship between sand size and beach face slope. Trans Am Geophys Union 32:866–874

Bitinas A, Žaromskis R, Gulbinskas S, Damušytė A, Žilinskas G, Jarmalavičius D (2005) The results of integrated investigations of the Lithuanian coast of the Baltic Sea: geology, geomorphology, dynamics and human impact. Geol Quart 49(4):355–362

Bobykina V, Boldirev V (2008) Tendency in shore dynamics in the Kaliningrad oblast according to 5 years monitoring information. In: International conference “Integrated management, sustainable development indicators, spatial planning and monitoringo of the South-Eastern Baltic coastal regions", March 26–30, 2008, Kaliningrad, Russia, pp 46–47 (In Russian)

Boldirev VL (1998) The Curonian Spit: the condition of the coastal zone and problems of coastal protection. In: Problems of investigation and protection of nature at the Curonian Spit, pp 87–99 (In Russian)

Bristow CS, Pucillo K (2006) Qantifying rates of coastal progradation from sediment volume using GPR and OSL: the Holocene fill of Guichen Bay, south-east South Australia. Sedimentology 53:769–788

Burnashov E, Scherbina V (2008) Geoinformationprovision of problemsof reservoir coastal zone management. In: International conference "Integrated management, sustainable development indicators, spatial planning and monitoringo of the South-Eastern Baltic coastal regions", March 26–30, 2008, Kaliningrad, Russia, p 53 (In Russian)

Costas S, Ajelo I, Rial F, Lorenzo H, Nombela MA (2006) Cyclical evolution of a modern transgresive sand barrier in northwestern Spain elucidated GPR and aerial photos. J Sediment Res 76:1077–1092

Dubois RN (1972) Inverse relation between foreshore slope and mean grain size as a funkcion of the heavy mineral content. Geol Soc Am Bull 83:871–876

Eberhards G, Grine I, Lapinskis J, Purgalis I, Saltupe B, Torklere A (2009) Changes in Latvia's seacoast (1935–2007). Baltica 22(1):11–22

Gudelis V (1998) The Lithuanian offshore and coast of the Baltic Sea. Lietuvos mokslas, Vilnius, p 439 (In Lithuanian)

Gudelis V, Kőnigsson LK (eds) (1979) The quarternary history of the Baltic. Almqvist & Wiksell Int, Stocholm, p 280

Hine AC (1979) Mechanisms of berm development and resulting beach growth along a barrier spit complex. Sedimentology 26:333–351

Hsu TW, Wang H (1997) Geometric characteristic of storm beach profiles. J Coastal Res 13(4):1102–1110

Jarmalavičius D, Žilinskas G (2001) Dependence of wash away during hurricanes on the coastal morpholithological indicators. Geografijos metraštis 34(1):88–94 (In Lithuanian)

Jarmalavičius D, Žilinskas G (2002) Recent trends of continental beach duneridges dynamics. Geografijos metraštis 35(1–2): 61–67 (In Lithuanian)

Karaliūnas V (1987) Morphodynamic processes on a sandy beach of the Baltic Sea south-east sector in different storm phases. Trudy Akad Nauk Lit SSR B serija 3(160):117–122 (In Russian)

Kirlys V (1967) On the question of short-period changes of sea beach cross-profile and the contour of the shoreline in shallow off-shore-water condition (the spit of Kuršių Nerija). Trudy Akad Nauk Lit SSR B serija 1(48):233–243 (In Russian)

Kirlys V, Stauskaitė R (1979) Volumes and rates of wash out and accumulation of beach sands during short term storm on shore of the south-eastern Baltic of transit character. Trudy Akad Nauk Lit SSR B serija 4(113):141–150 (In Russian)

Kirlys V, Stauskaitė R (1981) Rates of wash-out and accumulation of drifts on sandy beach on the south-east sector of the Baltic Sea in different phases of waves. Trudy Akad Nauk Lit SSR B serija 5(126):127–138 (In Russian)

Kirlys V, Močiekienė S, Janukonis Z (1981) Intensity of lasting storm changes of beach and protective dune ridge on shallow sandy sea coast of the south-east part of the Baltic Sea. Trudy Akad Nauk Lit SSR B serija 1122:101–108 (In Russian)

McLean RF, Kirk RM (1969) Relationship between size, size sorting and foreshore slope on mixed sand-schingle beaches. NZJ Geol Geophys 12:138–155

Musielak S (1989) Morpholithodynamics of the sandy sea beaches. Studia i materialy oceanologiczne, brzeg morski 1:67–78 (In Polish)

Pena HG, Lanfredi NW (1988) Beach profile analysis by empiric orthogonal functions. J Coastal Res 4(3):457–463

Povilanskas R, Baghdasarian H, Arakelyan S, Satkūnas J, Taminskas J (2009) Secular morphodynamic trends of the holocene dune ringe on the Curonian Spit (Lithuania/Russia). J Coastal Res 25:209–215

Pruszak Z, Schönhofer J, Skaja M (2008) Variability of shoreline and dune on south Baltic coast. In 9th International conference LITORAL 2008. A changing coast: challenge for the environmental policies, p 1–9

Shibayama T, Horikawa K (1985) A numerical model for two-dimensional beach transformation. Proc of JSCE 357:167–176

Short AD, Hesp PA (1982) Wave, beach and dune interactions in southeastern Australia. Mar Geol 48:8–16

Swain A, Houston JR (1984) A numerical model for beach profile development. Can J Eiv Eng 12(1):231–234

Swart DH (1991) Beach nourishment and particle size effects. Coast Eng 16(1):61–81

Tamura T, Murakami F, Nanayama F, Watanabe K, Saito Y (2008) Ground-penetrating radar profiles of Holocene raised-beach deposits in the Kujukuri strand plain, Pacific coast of eastern Japan. Mar Geol 248(1–2):11–27

Thom BG, Hall W (1991) Behavior of beach profiles during accreation and erosion dominated periods. Earth Surf Proc Land 16:113–127

Türker U, Kabdasli MS (2006) The effect of sediment characteristic and wave height on shape-parameter for representing equilibrium beach profiles. Ocean Eng 33:281–291

Wiegel RL (1964) Oceanographical engineering. Englewood Cliffs, Prentice Hall, New Jersey, p 532

Zawadzka E (1989) Morphodynamics of selected coastal segments of dune beach. Studia i materialy oceanologiczne 55:45–66 (in Polish)

Žilinskas G (1994) Coast condition and dynamics. In: Naftos terminalas Būtingėje: (ekologinė situacija). Baltic ECO, Vilnius, pp 121–137 (In Lithuanian)

Žilinskas G (1997) The length of the Lithuanian shore of the Baltic Sea. Geografijos metraštis 30:63–71 (In Lithuanian)

Žilinskas G (2005) Trends in dynamic processes along the Lithuanian Baltic coast. Acta Zoologica Lituanica 15(2):204–207

Žilinskas G, Jarmalavičius D (1997) Morphometric characteristics of the Lithuanian coasts of the Baltic Sea. Geografija 33:64–71 (In Lithuanian)

Žilinskas G, Jarmalavičius D (2000) Coast condition and dynamics. In: Klaipėdos uostas: ekonomika ir ekologija. Baltic ECO, Vilnius, pp 55–67 (In Lithuanian)

Žilinskas G, Jarmalavičius D (2003) Trends of Lithuanian sea coast dynamics. Geografijos metraštis 36(1):80–88 (In Lithuanian)

Žilinskas G, Jarmalavičius D, Kulvičienė G (2000) Assessment of the effects of hurricane "Anatolijus" on the Lithuanian marine coast. Geografijos metraštis 33:191–206 (In Lithuanian)

Žilinskas G, Jarmalavičius D, Minkevičius V (2001) Eolian processes on the marine coast. Institute of geography. Vilnius, p 283 (In Lithuanian)

Žilinskas G, Jarmalavičius D, Pupienis D (2005) Assessment of the effects of hurricane "Ervinas" on the Lithuanian marine coast. Geografijos metraštis 38(1):47–63 (In Lithuanian)

Žilinskas G, Jarmalavičius D, Pupienis D (2008) The impact of replenishment of beach sediments in the Palanga recreational zone on the state of coast. Annales Geographicae 41(1–2):50–66 (In Lithuanian)

Žilinskas G, Pupienis D, Jarmalavičius D (2010) Possibilities of regeneration of Palanga coastal zone. J Environ Eng Landsc Manag 18(2):95–101