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Main patterns of coastal zone development of the Curonian Spit, Lithuania

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Abstract The Curonian Spit is the largest sandy barrier on the Baltic Sea coast. The accumulation of the sand was caused mainly by alongshore sediment drift affecting a shore zone more than 600 km long from the Sambian Peninsula in the south to the mouth of the Gulf of Riga in the north. Although alongshore sediment drift presents a well–expressed South–North resultant, some parts of the south-eastern Baltic shore are developed rather differently due to changing natural and anthropogenic conditions. The paper analyses the peculiarities of the relief and sediment composition of the Lithuanian part of the Curonian Spit coastal area embracing the underwater sand bars, beaches, and fore-dunes. Trends in morphology changes and distribution of sediments in three dynamically different shore segments –relatively stable, transitional and accumulative –are discussed.

Keywords *Coastal area, beach, fore-dune, sand bar, long-shore drift, sediments, Curonian Spit, Lithuania.*

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INTRODUCTION

Accumulative type of the shores of Hell, Vistula and Curonian spits is one of the characteristic features observed at the sandy coasts of the south–eastern and southern Baltic (Boldyrev *et al.* 1976). The beginning of the spit system formation is associated with intensive sand accumulation during the regression of Ancylus Lake (Kabailienė 1967). Further development of the spits was significantly influenced by changing water level and oscillations of shoreline position (Gelumbauskaitė 2000; Gelumbauskaitė, Šečkus 2005; Gelumbauskaitė 2009). The longest accumulative shore segment extended about 98 km was identified in the Curonian Spit. Therefore, a multiple bar system is well–expressed at the nearshore that is very typical for sandy shores (King 1972). Such phenomenon is also observed at the sandy coasts of French Aquitanian (Castelle *et al.* 2007), Denmark (Ruessink, Terwindt 2000; Aagaard *et al.* 2010) and elsewhere.

The Curonian Spit is being investigated by researchers dealing with coastal zone over centuries. At the end of the nineteenth and the beginning of the twentieth centuries German hydro-engineering specialists (Abromeit *et al.* 1900) tried to determine methods how to prevent the shore erosion. At that time, about two hundred groynes had been built at the nearshore of the northern part of the Sambian Peninsula and southern part of the Curonian Spit (Aibulatov, Bass 1983). In the middle of twentieth century those groynes had already no environment protective effect (Boldyrev 1998). In the second half of the twentieth century northern part of the Sambian Peninsula and southern part of the Curonian Spit were reinforced by number of various engineering systems, which changed significantly the lithodynamical situation of the shores in the Sambian Peninsula and the Curonian Spit.

A so–called SE Baltic alongshore sediment drift takes place at the south–eastern shores of the Baltic Sea (Knaps 1966; Gudelis *et al*. 1977). The zone of sand supply covers all the northern shore of the Sambian Peninsula, starting from the Taran Cape (former Brüsterort), as well as the southern part of the Curonian Spit. The final discharge zone of the more than 600 km long sand drift is far north at the point of Kolkas Rags and the Gulf of Riga (Latvia). The area affected by the littoral drift is characterized by shore segments of different morphodynamic and geodynamic features. Different geodynamic regime appears even in a shore segment that, at the first sight, looks homogenous, i.e., the Curonian Spit. Its southern part, where littoral transport is not saturated with sediments, erosive pattern of the shore development is detected. While its middle part is in the dynamical equilibrium and, therefore, it is characterised by alternating erosion and accretion. Accumulation of sediments is prevailing in the northern part of the sand spit (Žaromskis, Kirlys 1989; Janukonis 1994).

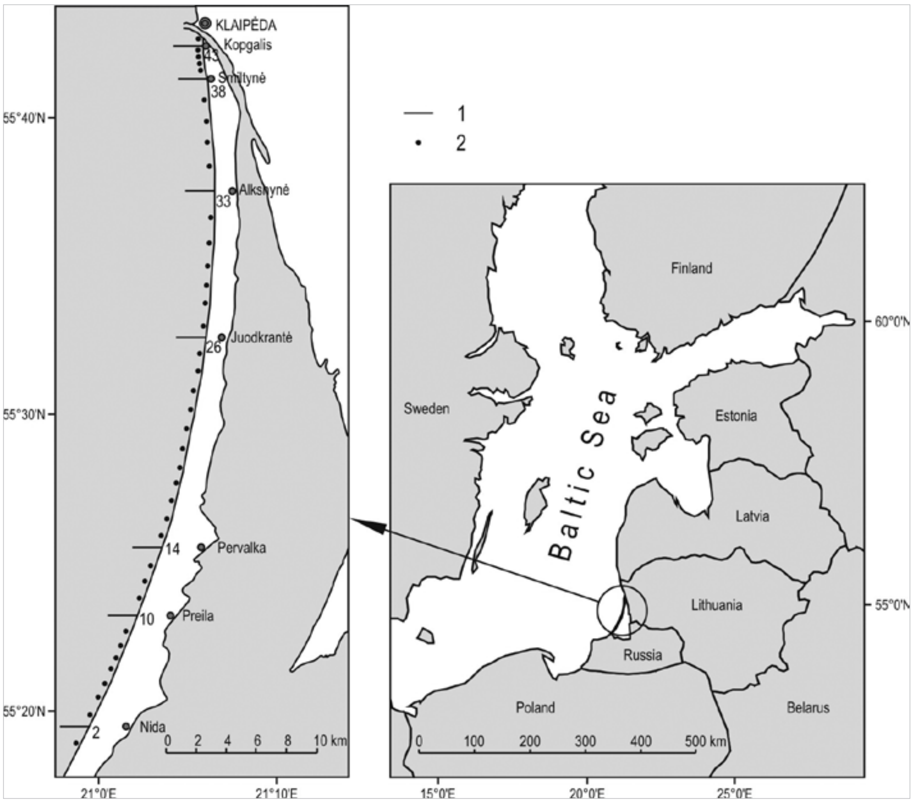

Fig. 1. Study site. 1 – profiles, selected for detailed analysis, 2 – location of investigated profiles. Compiled by S. Gulbinskas, 2010.

Various aspects of the shores of the Curonian Spit were studied. Some authors have analysed the shore zone as a space of alongshore sediment transport manifestation and distribution of drift energy characteristics (Knaps 1966; Gudelis *et al.* 1977; Kirlys 1968). Other authors directed their attention to the physical effect of the littoral drift on the shore (Boldyrev 1992a; Kirlys 1968). The rest studied distribution and genesis of sedimentary cover (Gelumbauskaitė, Šečkus 2005; Trimonis *et al.* 2007). Quite detailed analyses of the coastal aeolian formations were also performed (Žilinskas *et al.* 2001). Recently, some works covering nearly all the underwater slope appeared. For the first time investigations embraced not only the nearshore but also the offshore (Gelumbauskaitė 2003; Gelumbauskaitė 2007). There were attempts to correlate different expressions of morphodynamics and lithodynamics (Jarmalavičius, Žilinskas 2006; Žilinskas, Jarmalavičius 2007).

The goal of the present paper is to reveal the changes of lithodynamic and morphodynamic features of separate shore parts on the Lithuanian coast of the Curonian Spit affected by the long-shore sediment transport and developed under varying natural and anthropogenic conditions.

MATERIAL AND METHODS

The present work is based on the data obtained during the investigations of the Lithuanian part of the Baltic Sea coast in 2002–2004, and, partially, in 2006. The whole coastal zone of Curonian Spit including underwater slope down to a depth of 15 m has been studied. Sediment samples from the underwater slope were taken at depths of 1, 2, 3, 5, 7, 10 and 15 m (Fig. 1). The levelling of the beach and the fore-dune profile was performed, and sediment samples were taken at the centre of the beach and at the shoreline. 44 profiles were analysed in total. The all nearshore profiles were oriented in latitudinal (W-E) direction, whereas their continuation on the onshore was oriented in perpendicular to the shoreline. Grain size composition of sediments was determined using a standard dry sieving method for 23 fractions (from ≥ 0.05 mm to ≥ 10 mm). The median (*Md*) and sorting (*So*) parameters were calculated using Trask method (Trask 1930). Fore-dune height, beach width, bar zone width, depth of bars and troughs, declination of nearshore seaward the bar zone down to a depth of 15 m were analysed.

A resemblance procedure (Euclidean distance) and further non-metric multi-dimensional scaling (MDS) (Clarke, Warwick 1997) was applied to derive groups of profiles according to seven variables: *Md* of sediments at depths of 7 and 10 m, bar zone width, declination of nearshore slope seaward the bar zone, number of the bars, beach width and fore-dune height. These variables were intended to reflect the variation of general lithodynamical situation and shore morphology along the littoral transport from the south to the north. *PRIMER 6* (PRIMER-E Ltd.) statistical package was used for data analysis.

RESULTS

The MDS based resemblance analysis reveals consistent gradient changes of profile characteristics along the shore of the Curonian Spit (Fig. 2). All 44 profiles were grouped into three clusters: the 1st includes, with some exceptions, profiles from 2 to 12; 2nd – from 14 to 35; and 3rd – from 36 to 44. Seven profiles, representing three clusters were selected for further comparative analysis of the morphology profiles of underwater slope and shore as well as grain size composition. Two profiles were selected for the 1st cluster at Nida (2) and Preila (10), three profiles for 2nd cluster at Pervalka (14), Juodkrantė (26) and Alksnynė (33) and two for 3rd cluster at Smiltynė (38) and Kopgalis (43).

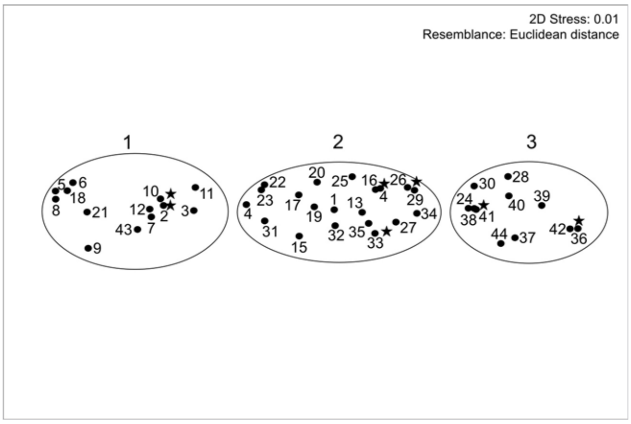

Fig. 2. Results of resemblance of 44 profiles (those selected for the further analysis are marked by an asterisk). Compiled by S. Gulbinskas, 2010.

A clear underwater slope with two well expressed bars has formed in the middle part of the shore in the Curonian Spit at the settlement Nida (Fig. 3). The width of nearshore bar zone is 563 m. The maximum relative height of the most distinctive outer bar reaches 5.5 m. At this bar, the most expressed differences in grain size of sediment particles on the bar top and the bottom of troughs are observed. At the bottom of the troughs, often, well–polished pebble and gravel is observed.

At Preila (about 10 km north of Nida), the cross-shore profile of the bar zone slightly differs from that at Nida. In general, profile retains the same character, although of a smaller scale. The relative height of the outer bar is also considerable (4.8 m) at Preila; moreover, the bar zone is even wider than that at the Nida nearshore and reaches about 600 m in width (Fig. 3).

The investigations of the shore showed that the width of the beach ranges, as a rule, from 30 to 35 m, but often reaches even 40-45 m (Fig. 4). At Nida it is often wider than in the northern part of the spit. The Nida beach sediments consist of sand of 0.25-0.315 mm grain size with gravel and pebble admixture. The beach northwards of Nida becomes slightly narrower but the height and mass of fore-dune is gradually growing.

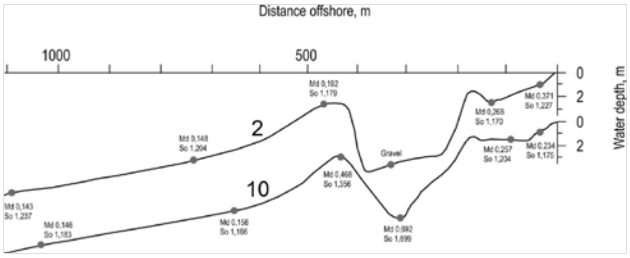

Fig. 3. Profiles of the underwater slope and grain size parameters (*Md* and *So*) of bottom sediments at Nida (2) and Preila (10). Compiled by R. Žaromskis and S. Gulbinskas, 2010.

Bottom profiles at Pervalka (6.5 km north of Preila), Juodkrantė and Alksnynė were attributed to the 2nd group (Fig. 5). The sand bars are well–expressed, but comparatively smaller than in the profiles belonging to the 1st cluster. The width of the bar zone is 470 m, and height of the outer bar is 3.3 m. Very well expressed morphology of the bar zone as well as pronounced difference of grain size of sediments of positive and negative bottom morphology forms is a general feature of the nearshore of the middle part of the Curonian Spit. Moreover, the grain size composition shows perfect differentiation of sediments along the cross-shore profile.

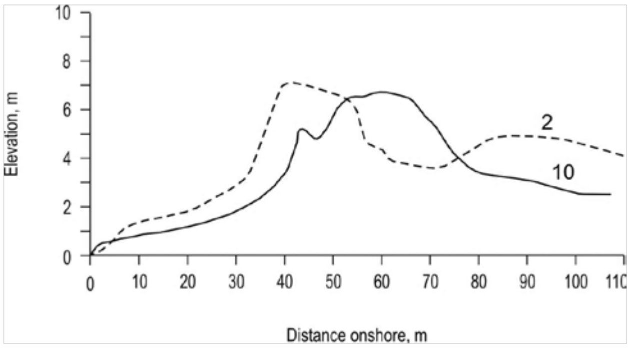

Fig. 4. The beach and fore-dune profiles of the shore at Nida (2) and Preila (10). Compiled by R. Žaromskis, 2010.

According to the cross-shore profiles, the nearshore morphology at Juodkrantė resembles that in Pervalka, but the relief forms are slightly smaller (Fig. 5). The bar zone here is just 375 m wide and the relative height of the biggest outer bar is 2.8 m.

Northwards from Juodkrantė, the further fining down of relief forms of the nearshore was observed (Fig. 5). Thus, 9.5 km northwards, the bar zone on the underwater slope at Alksnynė is represented by five bars. The total width of the bar zone reaches 540 m. These bars are significantly smaller than those in the middle part of the Curonian Spit. General differentiation of sediment grain size composition along the profile still retains similar character as it is on the southern parts. Sediments in the trough differs from the adjacent uniform fine sand formation by roughness (*Md* is 0.6 mm) and low sorting (*So* is 1.6). Sediments on the bottom surface of the underwater slope are rather uniform. *Md* of samples taken from the top of the bars or troughs is ranging just from 0.18 mm to 0.26 mm. The sorting coefficient (*So* is 1.38) shows that material of various generations occurs in the troughs. The diversity of the sedimentation is herewith representative for the whole sediment thickness. In general differentiation of the sediments according to the grain size and along the cross-shore profile is better expressed in the whole profile at Juodkrantė than one of the bar zone itself described above. *Md* coefficient changing from 0.16 mm at a depth of 10 m to 0.22 mm at a depth of 1 m is a clear evidence of that.

The height of the fore-dune gradually increases northwards from Pervalka to Juodkrantė where relative height increases from 7-9 m (at Pervalka) to 8-11 m (at Juodkrantė) (Fig. 6). However, there are places where the fore-dune height is not reaching more than 7-8 m above the sea level. Beach width at this part of the coast reaches 35-45 m. Fine grained sand is prevailing (*Md* 0.21 mm) with considerable admixture of medium grained sand (Fig. 7).

The nearshore at Smiltynė has well–expressed zone of bars and troughs having about 400 m width in total. The height of the bar that lies most distant from the shoreline reaches 2 m (Fig. 8). The morphology of bar zone is pictured by a rather chaotic and irregular set of bars and troughs. The roughness of sediments changes slightly with the depth –*Md* is 0.21 mm at a depth of 1 m and 0.12 mm at a depth of 15 m. At Kopgalis, the underwater slope distinguishes itself by a small gradient as well as by untypical nearshore cross-shore profile of the bar zone and varying number of bars. There is no marked differentiation of the sediments on the underwater slope going deeper.

If going further northwards, the morphology features of the nearshore are gradually fining down. The shore part above the water has contrary an opposite picture, i.e., beach width increases and often exceeds 60 m, and the fore-dune height reaches 12 m (Fig. 9). In the northern part of the Curonian Spit height and/or dome-shaped top of the fore-dune should not be considered as representative feature. Particular characteristic of the fore-dune is represented by well–expressed terraces visible in a transverse profile showing periodical character of fore-dune development.

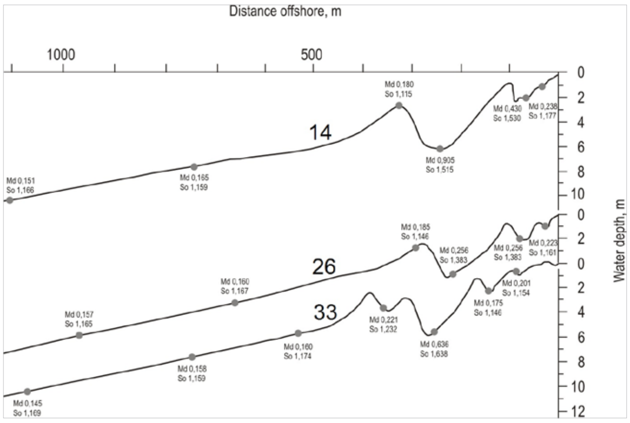

Fig. 5. Profiles of the underwater slope and grain size parameters (*Md* and *So*) of bottom sediments at Pervalka (14), Juodkrantė (26) and Alksnynė (33). Compiled by R. Žaromskis and S. Gulbinskas, 2010.

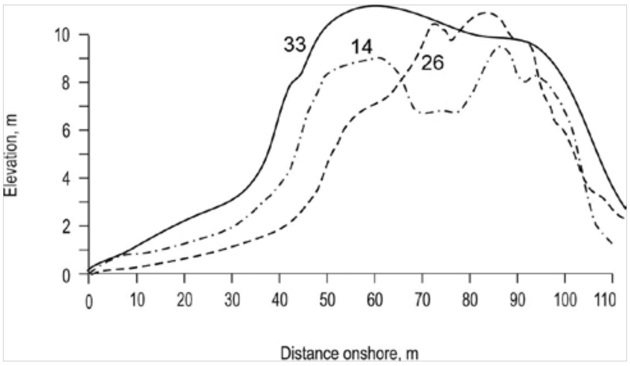

Fig. 6. The beach and fore-dune profiles of the shore at Pervalka (14), Juodkrantė (26) and Alksnynė (33). Compiled by R. Žaromskis, 2010.

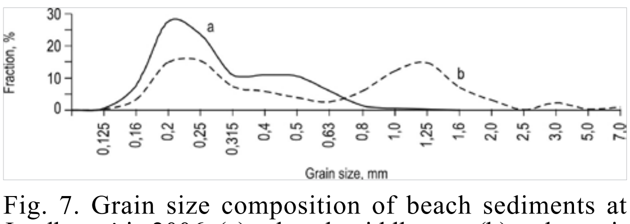

Fig. 7. Grain size composition of beach sediments at Juodkrantė in 2006: (a) at beach middle part; (b) at dynamical shoreline. Compiled by R. Žaromskis, 2010.

DISCUSSION

The formation of the coastal zone on the Curonian Spit is caused by both natural and anthropogenic factors. Among the natural factors, an important role is played by severe storms, which become more frequent, although this should not be overestimated either. According to the Lithuanian Hydrometeorological Service continuous observation data on average diurnal wind speed for the period of 1926–1935, there were 11 cases when wind speed reached 24 m/s and only once the wind reached 28 m/s. In 1948–1957, there were 13 cases of wind speed reaching 24 m/s and 10 cases of 28 m/s, but there were even 9 cases recorded when wind speed exceeded 32 m/s. In 1981–1989, the meteorological conditions were close to the ones beginning in the twentieth century. Thus, the wind speed of 24 m/s was observed only 5 times and 28 m/s wind was identified 3 times. During the periods of calm and moderate sea, sand accumulation take place at the shore, while under the rough sea conditions the erosion of shore prevails. Periodically changing conditions determines the pattern of the sediments balance and littoral drift in a certain parts of the shore. According to the data available, it seems that strong winds and even storms have been present also during the mid of the twentieth century, but the negative effects on the shore was less than those occurred at the end of the twentieth century or the beginning of the twenty first century.

Water level changes also play an important role in development of the shore. From 1970s the Baltic Sea level rose by 14-15 cm (Johansson *et al.* 2001; Dailidienė *et al.* 2006).

During the second half of the twentieth century, the conditions of the sediment supply to the alongshore sediment transport changed significantly in the SE Baltic Sea. The availability of sand resources dramatically decreased on the northern nearshore of the Sambian Peninsula (Boldyrev 1992b; Zhamoida *et al.* 2009). The movement of sediments was blocked by stabilising the shore by rigid engineering structures in the northern part of the Sambian Peninsula and the southern part of the Curonian Spit. Therefore, the zone of shore erosion and consequentially the sand supply zone shifted northwards. As the result intensified erosion is observed at the 25 km long-shore segment at the southern part of the Curonian Spit (Orlenok, Fedorov 2005). However, this zone of active erosion has not reached yet the Lithuanian part of the Curonian Spit and does not trigger significant morphodynamic and lithodynamic changes.

A human activity at the northern ending of the Curonian Spit where Klaipėda state seaport is built-up also influences the conditions of shore development. The critical action was taken when a port entrance channel was made deeper by dredging to 14.5 m. This work has increased inclination of the underwater slope profile and activated sediments migration seawards. The erosion of the shore at Kopgalis began. The beach became narrower and profile -flatter. The erosion of the base of fore-dune became more often (Žilinskas 1998). In 2002 the second part of port entrance channel development took place –southern breakwater was extended by 300 m seawards. Sediment migration conditions have been changed once again.

Before the reconstruction of the harbour gate, fine sand used to bypass the piers and the channel at depth of 13 m approximately (Žaromskis 1999). After the reconstruction the northward load transport was impeded greatly (Žaromskis 2007), and the sediment migration area moved farther beyond the closure depth (Vellinga 1983). On the other hand such a situation has created conditions favourable for sediment accumulation south from the port entrance gates that accretion effect reaches even Juodkrantė. This is reflected in the morphology of the shore and the underwater slope (Figs 8, 9).

The locally occurring erosion of the shore at the very pier does not change the general tendency of accumulation that is characteristic of the northern part of the Curonian Spit. The changed conditions are reflected in the grain size composition of sediments. Hence, *Md* values of sediments on the underwater slope at Kopgalis increased from 0.07-0.08 mm in 1973 (Žaromskis 1974) to 0.13-0.18 mm in 2003.

Although the sedimentation conditions are changing in the southern and northern parts of the Curonian Spit, the northward oriented littoral drift safeguards rather stable morphology of the shore zone in the middle part of the sand spit. Usually the processes of

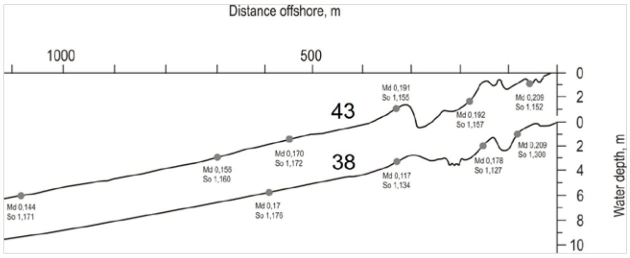

Fig. 8. Profiles of the underwater slope and grain size parameters (*Md* and *So*) of bottom sediments at Smiltynė (38) and Kopgalis (43). Compiled by R. Žaromskis and S. Gulbinskas, 2010.

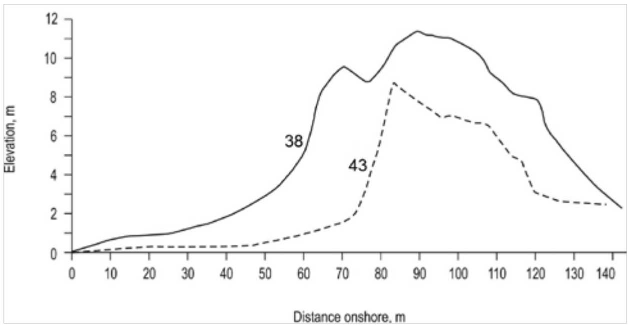

Fig. 9. The beach and fore-dune profiles of the shore at Smiltynė (38) and Kopgalis (43). Compiled by R. Žaromskis, 2010.

accretion and erosion interchange. This fully corresponds to the morphological indicators of long-shore sediment drift typical for the sediment transit areas (Boldyrev 1998).

Direction of waves plays an important role as well. Waves of WNW–NNW directions are the ones that form a well–expressed southward orientated littoral drift. Such conditions are favourable for the sediment accumulation in the shore parts between Nida and Pervalka, as well as in the southern (Russian) part of the Curonian Spit. And opposite, when waves of W–SW directions are active the shore erosion is observed in the middle and southern parts of the Curonian Spit (Žaromskis, Kirlys 1989). This phenomenon is caused by different conditions in the zones of sediment load mobilisation during their northward or southward transportation. Some authors (Blazhchishin *et al.* 1982; Boldyrev 1992a) note that the underwater slope at the southern parts of the sand spit have only a thin layer of loose sediments, and till loam is exposed on the bottom of some sites. Therefore, the northward stream of sediments is becoming saturated in an approximately 55 km shore zone of the Sambian Peninsula and the Curonian Spit. There is a large sand deposit accumulated at the northern part of the spit. Under NW winds, the southward littoral drift becomes saturated in a 10-15 km long-shore section, starting from a point south of Alksnynė and extending to a point south of Juodkrantė. Therefore, the dynamical equilibrium (sediment transit) in the middle part of the Curonian Spit persists in the shore even at different littoral drift directions (Fig. 10).

The scheme explain quite well the distribution of shore segments with different dynamic pattern

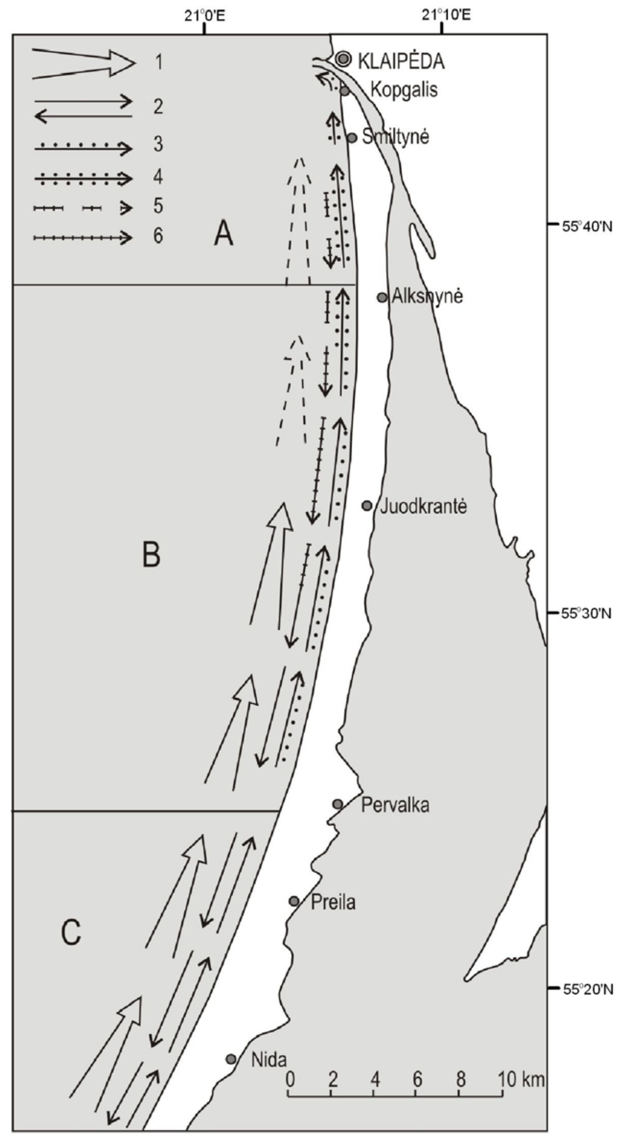

Fig. 10. A scheme of lithodynamical processes at the shore of Curonian Spit (Lithuanian part). A, B and C – lithodynamical sectors; 1 – littoral drift; 2 – potential directions of sediment transport; 3 – partial accumulation; 4 – stable accumulation; 5 – partial mobilisation; 6 – stable mobilisation. Compiled by R. Žaromskis, 2010.

–erosive, stable and accretion but it is not clear yet why the nearshore morphology of the bars in the middle part of the spit is better expressed, bar zone is wider, and distances between the bar tops gradually decreases northwards of Preila. After all, there is no sediment deficit at the Lithuanian nearshore at the Curonian Spit. A sediment field of rather similar grain size composition prevails in the nearshore part of the underwater slope between the bar zone and the 15 m isobath, where *Md* and bottom inclination (*tgα*) range usually from 0.12 to 0.14 mm and from 0.007 to 0.01, correspondingly. A slight increase of bottom inclination between the 15 m isobath and bar zone is also observed at Juodkrantė–Pervalka shores. Here the value of *tgα* increases from 0.0086 (the average for all Lithuanian coast of the Curonian Spit) to 0.0095. This factor can favour the waves to reach the shore at the Juodkrantė–Pervalka part with higher energy than in the adjacent areas. Nevertheless, it should not cause significant changes in shore morphology and grain size composition of sediments.

Development of the bars in the nearshore can be determined by various factors. Firstly, their distribution is related to breaking waves (Egorov 1951); ratio of settling rate of sediments raised by a breaking wave and the wave period (Dean 1985); average height of an open sea wave (Kraus *et al.* 1991). Some authors relate the formation of bars with the closure depth (Roelvink, Steve 1989) that should result in bars appearing at the depth slightly exceeding 6 m at the Curonian Spit nearshore. And this is true for the outer bar in the middle part of the Curonian Spit, i.e., Nida–Pervalka nearshore. The most seaward located outer bar is identified at a depth of 6-7 m. Going northwards, the bottom inclination changes a little, but the outer bar is formed at depths of 4, 3 or even 2 metres.

Formation of bars is also related to the impact of local periodical changes of water level in the nearshore (O'Hara, Hyntley 1994). I. Leontiev explains the phenomenon of bar formation as a result of dissipation of wind wave energy when the waves break (Leontiev 2004). This takes place in the nearshore during weak and low frequency oscillations of water level. According to I. Leontiev, the distance between bar tops in the cross-shore transverse profile should correspond to the length of long-period waves. Nevertheless, it remains unclear why the length of such long-period waves differs in Preila and Pervalka, which is just 6.5 km away. Thus the morphology of underwater slope cannot be explained merely by wave field peculiarities.

Full development of bar zone is related to the capacity of the littoral drift (Boldyrev 1992b). A similar opinion has been expressed by R. Knaps, who attributes an important role of the alongshore currents (Knaps 1981). Undoubtedly, the alongshore drift of water masses and sediments affects the meso-scale oscillation of water level. But the same phenomenon wouldn't be characteristic for middle part of the Curonian Spit nearshore only. On the contrary, it should spread at least up to the area with well–expressed sediment accumulation. However, the sediment transport is blocked northwards by harbour piers at the northern part of the Curonian Spit.

The exposition of the shoreline to the prevailing winds is important for water mass circulation and nearshore lithodynamics. It determines the angle of the waves approaching the shore. If the morphology of bar zone is determined only by this factor, i.e., the wave refraction degree, then, under favourable conditions, an expressive bar zone morphology should be formed at the traverse of Juodkrantė and Alksnynė. However, no such cases had been registered here ever. Therefore, the expressiveness of the bar zone morphology on the underwater slope, under similar lithological conditions would be expedient to relate to the processes of movement of water masses and sediment transport along the shoreline.

Analysing the morphodynamic peculiarities of underwater slope in the Curonian Spit, one encounters the processes of differentiation of sediments along the cross-shore profile. As the profiles presented show (see Figs 3, 5, 8), the grain size of sediments on the top of bars changes little, going along the nearshore from the south to the north. It was also observed that the coarser matter is present in the deepest part of the troughs only. Having in mind that there are no such coarse sediments in other places of the nearshore, it can be assumed that they occur only in the sediment bed formed under the lower levels of the sea (Trimonis *et al.* 2007) and they are not directly related to merely wave processes. Such coarse matter occurs in the troughs at the Nida–Pervalka shore part, but it is observed in other sites as well.

CONCLUSIONS

The coastal zone of the Lithuanian part of the Curonian Spit develops under the conditions of more and more frequent strong waves, water level rise and increased deficit of sediments transported along the shore in the southern part of the sand spit. The shore and alongshore sediment drift in the northern part of the Curonian Spit is affected by the hydro-engineering constructions of the Klaipėda harbour.

The dynamical equilibrium (transit or stable), intermediate and accretion segments are distinguished on the Lithuanian shore of the Curonian Spit. The segment of dynamical equilibrium is expressed by alternating accumulation of sediments and local events of erosion; six to eight metres high fore-dune and beach reaching width of 35 m; sediments with prevailing particles of 0.25-0.315 mm. The underwater slope of the shore is characterized by, at least, one very deep (up to 8 m) trough between the well-developed outer and inner bars and a wide bar zone.

The characteristics of identified as dynamically intermediate segments of the shore lying between those of dynamical equilibrium and sediment accumulation are: (1) wide bar zone but less expressed relief; (2) smaller differences in grain size between the sediments on bar tops and troughs. Beach width and fore-dune height ranges usually from 35 to 45 m and from 8 to 11 m, correspondingly. Going from the relatively stable shore parts to the accretion ones, the nearshore relief forms are fining, while those onshore are becoming better expressed.

The shore where accretion is prevailing occupies the northernmost part of the Curonian Spit. Here, a high dome-shaped fore-dune exceeds 12 m in some places, the beach is as wide as 70 m, and near shore has up to five low relief bars. The deposits accumulated at the southern (leeward) side of the harbour piers take only a small part in the lithodynamic circulation system of the whole Curonian Spit. At the shore segment adjacent to the pier sediments are being dragged away seawards and the erosion of the shore is happening.

The inclination of nearshore seaward the bar zone changes slightly. If going from the south to the north, the grain size of sediments remain nearly the same, and the depths above the outer bars range from 2.4 to 2.7 m. This indicates a similar dissipation of wave energy along the whole Curonian Spit nearshore.

Transit of sediments prevails in the middle part of the Curonian Spit. And this process is independent from the direction of the transit –northward or southward. In the case of the southward transit the middle part of the sand spit is fed better with sediments from the northern zones than during the north directed sediment drift. This is due to the smaller sand reserves in the southern zone.

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References

Aagaard, T., Kroon, A., Greenwood, B., Hughes, M. G., 2010. Observations of off-shore bar decay: sediment budgets and the role of lower shore face processes. *Continental Shelf Research 30,* 1497–1510.

Abromeit, J., Bock, P., Jensh, A., 1900. *Handbuch des deutshen Dünenbaues.* Berlin (Parey), 445 pp.

Aibulatov, N. A., Bass, O. V., 1983. Anthropogenic factors in the Baltic Sea coastal zone development. *Water Resources 3,* 127–134. [In Russian].

Blazhchishin, A. I., Boldyrev, V. L., Efimov, A. N., Timofeev, I. A., 1982. Ancient shore lines and shore formations in the south-eastern part of the Baltic Sea. *Baltica 7,* 57–64.

Boldyrev, V. L., Gudelis, V. K., Shuisky, Yu. D., 1976. Baltic Sea coasts and their role in sediment supplying. *In* V. K. Gudelis, E. M. Emelyanov (eds), *Geology of the Baltic Sea,* Vilnius, 141–158. [In Russian].

Boldyrev, V. L., 1992a. Morphologic and lithodynamic indicators of regions with developing along-shore drift of sand deposits. *In* K. Orviku (Ed.), *Study of main appropriateness and tendencies of the Baltic Sea coastal line changing during last 100 years*, Tallinn, 55–62. [In Russian].

Boldyrev, V. L., 1992b. Forming, development and modern dynamics of the Baltic Sea coast within Kaliningrad region. *In* K. Orviku (Ed.), *Study of main appropriateness and tendencies of the Baltic Sea coastal line changing during last 100 years*, Tallinn, 27–33. [In Russian].

Boldyrev, V. L., 1998. The Curonian Spit: the condition of the coastal zone and problems of coastal protection. *In* V. M. Slobodyanik, A. R. Manukyan (eds), *Problems of investigation and protection of nature at the Curonian Spit*, Kaliningrad, 87–99. [In Russian].

Castelle, B., Bonneton, Ph., Dupuis, H., Sénéchal, N., 2007. Double bar beach dynamics on the high-energy meso-macrotidal French Aquitanian coast: a review. *Marine Geology 245,* 141–159.

Clarke, K. R., Warwick, R. M., 1997. *Change in marine communities: an approach to statistical analysis and interpretation.* Plymouth, Plymouth Marine Laboratory, 144 pp.

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

Dean, R. G., 1985. Physical modelling of littoral processes. *In* R. A. Dalrymple (Ed.), *Physical modelling in coastal engineering*, A. A. Balkema, Rotterdam, 119–139.

Egorov, E. N., 1951. Dynamics of underwater sand bars. *Transactions of the Institute of Oceanology 66,* 56–81. [In Russian].

Gelumbauskaitė, L. Ž., 2000. Late- and Postglacial palaeogeomorphology on the Klaipėda submarine slope, south-eastern Baltic Sea. *Baltica 13*, 36-43.

Gelumbauskaitė, L. Ž., 2003. On the morphogenesis and morphodynamics of the shallow zone of the Curonian Spit. *Baltica 16,* 37-42.

Gelumbauskaitė, L. Ž., 2007. Sea shore underwater slope (nearshore) of Curonian Spit. *In* Climate change: adaptation to its impact at the Lithuanian seaside, Vilnius, 32–39. [In Lithuanian].

Gelumbauskaitė, L. Ž., 2009. Character of sea level changes in the subsiding south-eastern Baltic Sea during Late Quaternary. *Baltica 22 (1),* 23–36.

Gelumbauskaitė, L. Ž., Šečkus, J., 2005. Late Quaternary shore formations of the Baltic basins in the Lithuanian sector. *Geologija 52*, 34–45.

Gudelis, V., Kirlys, V., Močiekienė, S., 1977. Littoral drift regime and dynamics along the eastern coast of the Baltic Sea in the off-shore zone of the Curonian Spit according to the data of 1956–1974. *Transactions of the Lithuanian Academy of Sciences, Series B 4 (101),* 123–128. [In Russian].

Janukonis, Z., 1994. Structure relief and lithodynamic conditions in the coastal zone of the south-eastern Baltic Sea. *Geographical Yearbook 28*, 212–234. [In Lithuanian].

Jarmalavičius, D., Žilinskas, G., 2006. Peculiarities of sand sorting in the Lithuanian coast of the Baltic Sea. *Geologija 56*, 36–42.

Johansson, M, Boman, H., Kahma, K., Launiainen, J., 2001. Trends in sea level variability in the Baltic Sea. *Boreal Environment Research 6,* 159–179.

Kabailienė, M., 1967. The development of the Kuršių Nerija Spit and Kuršių Marios Lagoon. *Proceedings of Institute of Geology 5,* 181–207. [In Russian].

King, C. A. M., 1972. *Beaches and coasts*. Edward Arnold, London, 570 pp.

Kirlys, V., 1968. Intensity and direction of sediment transport along the Baltic coast of the Curonian Spit. *Transactions of the Lithuanian Academy of Sciences, Series B 3 (54),* 125–132. [In Russian].

Knaps, R. J., 1966. Sediment transport near the coasts of the Eastern Baltic. *In* Development of sea shores under the conditions of oscillations of the Earth's crust, Valgus, Tallinn, 21–29. [In Russian].

Knaps, R. J., 1981. Non-wave currents in the nearshore zone. *In* The shore zone of the sea, Moscow, 32–40. [In Russian].

Kraus, N. C., Larson, M., Kriebel, D. L., 1991. Evaluation of beach erosion and accretion predictors. *Proceedings of Coastal Sediments '91*, American Society of Civil Engineers, New York, NY, 572–587.

Leontiev, I. O., 2004. Equilibrium coastal profile and a multiple bar system. *Okeanologiya 44 (4),* 625–631. [In Russian].

O'Hara, T. J., Huntley, D. A., 1994. Bar formation due to wave groups and associated long waves. *Marine Geology 116*, 313–325.

Orlenok, V. V., Fedorov, G. M., 2005. *Regional geography of Russia.* Kaliningrad, 258 pp. [In Russian].

Roelvink, J. A., Stive, M. J. F., 1989. Bar generating cross-shore flow mechanisms in a beach. *Journal of Geophysical Research 94 (C4),* 4785–4800.

Ruessink, B. G., Terwindt, J. H. J., 2000. The behaviour of nearshore bars on the time scale of years: a conceptual model. *Marine Geology 163,* 289–302.

Trimonis, E., Gulbinskas, S., Blažauskas, N., Kuzavinis, M., Visakavičius, E., 2007. Composition and formation of sand massifs in the Curonian–Sambian submarine plateau (Baltic Sea). *Geologija 60,* 39–50.

Trask, P. D., 1930. Mechanical analysis of sediment by centrifuge. *Economic Geology 25,* 581–599.

Vellinga, P., 1983. Predictive computational model for beach dune erosion during storm surges. *Proceedings, American Society of Civil Engineers Speciality Conference on Coastal Structures 83,* 806–819.

Zhamoida, V., Ryabchuk, D. V., Kropatchev, Y. P., Kurennoy, D., Boldyrev, V. L., Sivkov, V. V., 2009. Recent sedimentation processes in the coastal zone of the Curonian Spit (Kaliningrad region, Baltic Sea). *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften 160 (2),* 143–157.

Žaromskis, R., 1974. Peculiarities of the relief of underwater bars: coastal zone of the Curonian Spit. *Geographical Yearbook 13,* 229–235. [In Lithuanian].

Žaromskis, R., 1999. Influence of Klaipėda port on the nearshore load migration. *Geografija 35 (1),* 20–27. [In Lithuanian].

Žaromskis, R., 2007. Impact of harbour moles and access channels on the south-eastern Baltic shore zone. *Geografija 43 (1),* 12–20. [In Lithuanian].

Žaromskis, R., Kirlys, V., 1989. Influence of wave propagation direction on prevailing processes of sand removal and accumulation in the coastal zone of the south-eastern part of the Baltic Sea. *Transactions of the Lithuanian Academy of Sciences, Series B 3 (172),* 138–141. [In Russian].

Žilinskas, G., Jarmalavičius, D., 1996. Estimation of vulnerability of the Lithuanian Baltic Sea coasts on the background of the Baltic Sea water level rise. *Geographical Yearbook 29,* 174–183. [In Lithuanian].

Žilinskas, G., 1998. The peculiarities of shoreline dynamics in the impact zone of Klaipeda port. *Geographical Yearbook 31,* 99–109. [In Lithuanian].

Žilinskas, G., Jarmalavičius, D., Minkevičius, V., 2001. *Eolian processes on the marine coast*. Vilnius, 283 pp. [In Lithuanian].

Žilinskas, G., Jarmalavičius, D., 2007. Interpretation of morphometric parameters of the submarine shore slope of the Curonian Spit, Lithuania. *Baltica 20 (1-2),* 46–52.