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Grain size variability as an indicator of sediment transport alongshore the Curonian Spit (south-eastern Baltic Sea)

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Abstract Sediment samples have been collected along the sea coast of the Curonian Spit in summer season of 2011, 2014 and 2015-years. According to grain size analysis the shoreline and the berm consist of well and very well-sorted sand, medium-sized on the southern (Russian) part of the spit, medium and fine on the northern (Lithuanian) part. ‘McLaren’ method was applied to determine the long-shore sediment transport directions. Mismatch of results with those obtained by methods based on simulation of resulted wave action did not prove the hypothesis that ‘McLaren’ method was able to reveal long-term resulted sediment transport. The hypothesis that ‘McLaren’ method indicates the directions of alongshore sediment transport during the stormy conditions preceding the sampling period was not proved also. It was concluded that application of ‘McLaren’ method in respect of the Curonian Spit shore, which is a transit one without permanent sources or sinks of sediments, is not efficient. ‘McLaren’ method was applied to describe the cross-shore sediment movement. It was found that deposits from the trough (located between the bar and shoreline) are transported to the shoreline that is in a line with the known fact about cross-shore transport of bottom material during the calm weather.

Keywords *• sediment transport • grain size analysis • grain-size distribution statistics •‘McLaren’ method*

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INTRODUCTION

The Curonian Spit (Tonisson *et al.* 2013) is an elongated sand peninsula, 98 km long and 0.35–0.8 km wide, located in the south-eastern part of the Baltic Sea (Fig.1). The spit is extended in north-north-eastern direction and separates the Curonian Lagoon from the Baltic Sea. The Russian-Lithuanian border divides the spit in two almost equal parts: Russian in the south, Lithuanian in the north. The Curonian Spit is a nature protected area and it is included in World Heritage List of UNESCO [http://whc.unesco.org/en/list].

There are two main hypotheses about the long-shore sediment transport along the Curonian Spit. The idea about mono-directed Eastern-Baltic northwards sediment flow from the Cape Taran along the Curonian Spit till the Cape Kolka was formulated by Knaps (Knaps 1952) and supported by scientists during decades. An opposite conception about existence of the counter flow was proposed in 1968 (Kirlys 1968). Starting from that time both hypotheses have been under discussions and the subject of studies (Žaromskis, Gulbinskas 2010; Viška, Soomere 2013; Krek *et al.* 2016; Pupienis *et al.* 2016).

Analysis of beach sediment grain-size distribution along the shore of the South-eastern Baltic (Agapov, Zhindarev 1990) pointed out the fragmentation of long-shore sediment flows within the limits of isolated morpholithodynamic cells. The studies based on application of an up-to-date numerical model provides a point of view that instantaneous direction of the sediment transport along the spit fully depends on wind and wave influence, but the ultimate annual flow has several convergence and divergence points along the Curonian Spit (Leont'ev, Akivis 2014), or a single convergence point that migrates year-to-year (Viška, Soomere 2013; Soomere, Viška 2014).

The aim of the study was to find some evidences of a general direction of sediment transport along and across the marine shore of the Curonian Spit explicitly based on alongshore and cross-shore changes in grain-size parameters (mean grain size, sorting and skewness) of surface sediments.

MATERIAL AND METHODS

The method proposed by P. McLaren and D. Bowles in 1985 (McLaren, Bowles 1985) was applied. It was supposed to reveal a direction of sediment transport based on grain-size distributions characteristics (mean, sorting and skewness) of the material deposited along the path of examined sediment transport. It was tested in estuaries and deltas (McLaren, Bowles 1985; Wu, Shen 1999) and other sediment environments with permanent water and consequently a sediment flow. The method was very widely-applied, for coastal zones included (McLaren 1981; Mohd-Lokman *et al.* 1998).

Sediment sampling

Sediment sampling was carried out in 2011, 2014 and 2015-years during summer season under calm-wind conditions. In 2011, sediment sampling was carried out during the 8–15th of August at 62 transects, each 500 m, north of Zelenogradsk on the Russian part of the Curonian Spit (Fig. 2). In 2014, sampling was implemented both on the Russian and Lithuanian parts of the Curonian Spit during the 4–5th of August and 11–12th of September respectively in total at 91 transects with a 1-km spatial step (42 km on the Russian side and 49 km on the Lithuanian side).

On the 22nd of June, 2015, only 7-km section of the coastline in the middle of the Russian part was inspected. Deposits (the only upper layer of 1–3 cm) were collected at nine cross-shore transects: at the last underwater bar (about 1 m deep), a trough between this bar and shoreline (about 1.5 m depth), the shoreline, middle part of the beach, upper part of the beach.

Assuming that the onshore wind higher than 10 m/sec with duration longer than six hours could produce reasonable alongshore sediment transport, we revealed periods of such wind actions that had taken place before the sampling periods (Table 1). Wind impacts prior to sampling of 2011 and 2014-years were similar, the wind blew onshore the Curonian Spit and contributed to the northward alongshore sediment

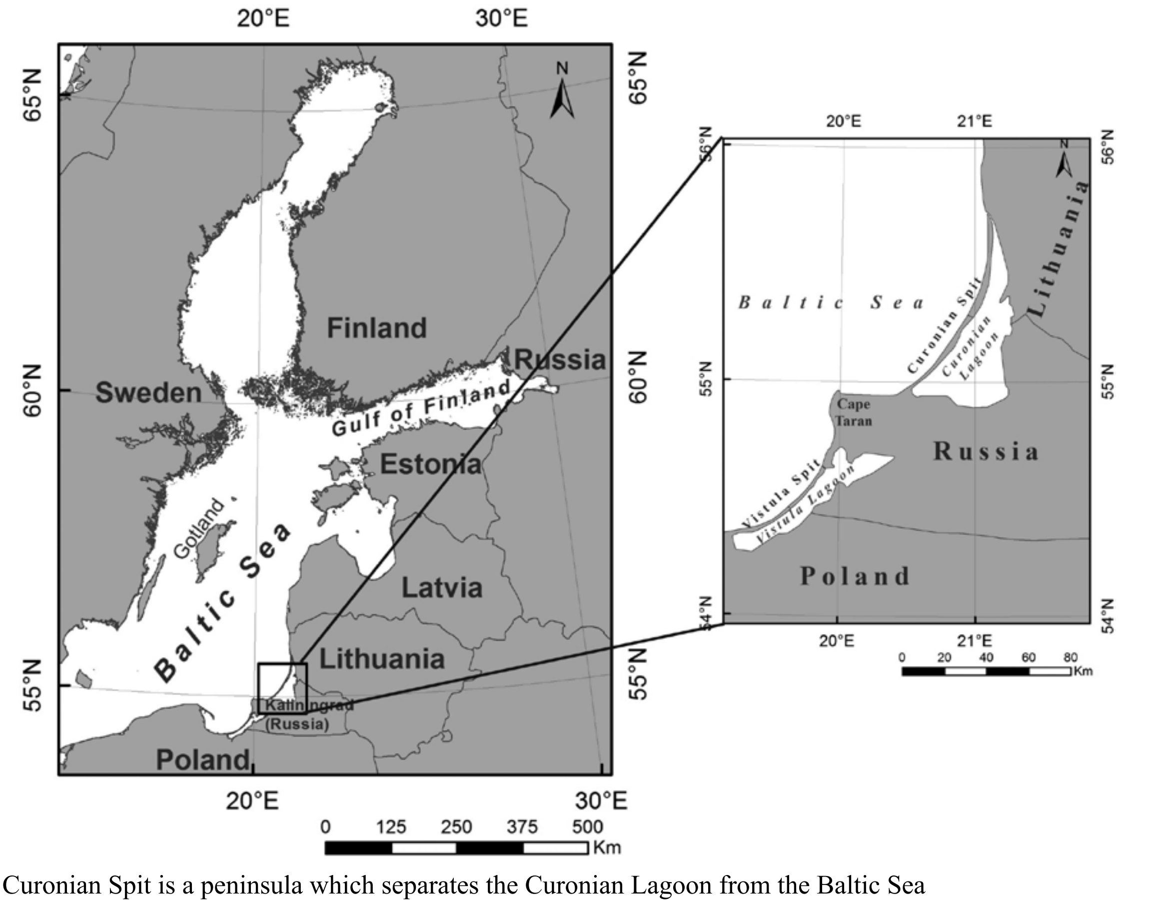

Fig. 1 Curonian Spit is a peninsula which separates the Curonian Lagoon from the Baltic Sea

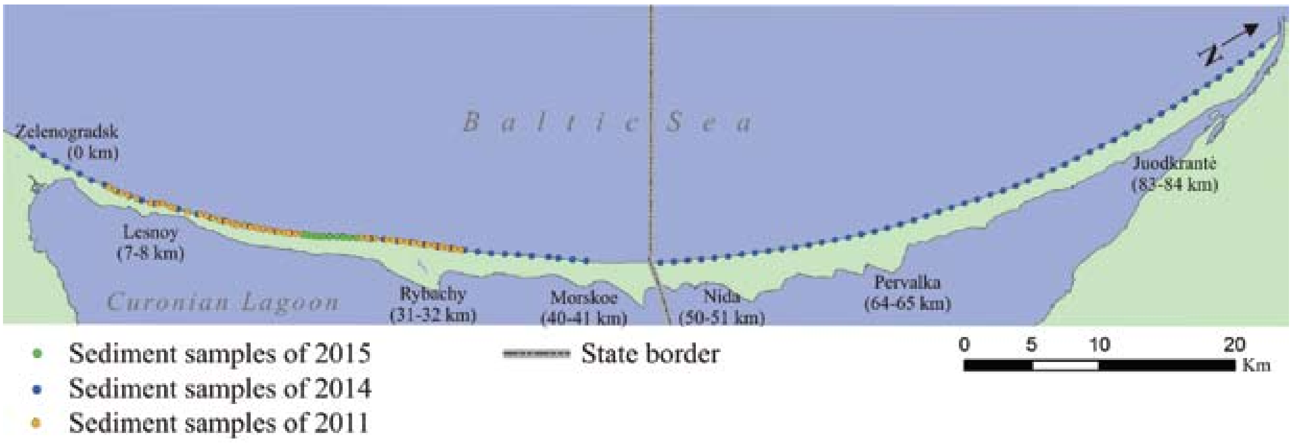

Fig. 2 Sediment sampling locations on the Curonian Spit in 2011, 2014 and 2015. Compiled by O. Kovaleva, 2015

transport. Two events related to opposite sediment transport happened one month before the sampling in 2015; it was southward transport on May 20, 2015 and northward transport on May 12–18, 2015.

Grain size and its statistical distribution

Sediment samples were subjected to sieve analysis (Romanovsky 1988; Kotelnikov 1989), which resulted in revealing the mass percentage content of 19 size grades (Udden 1914; Wentworth 1922), expressed in a form of range of particle diameter (mm) and *φ*. Three parameters of statistical distribution (mean grain size, sorting and skewness) were calculated for each sample according to logarithmic method of moments (Table 2). Qualitative estimation of sorting was made according to classification (Folk, Ward 1957), see Table 3.

Estimation of alongshore sediment transport direction according to 'McLaren' method

'McLaren' method (McLaren, Bowles 1985) considers variations in parameters of grain-size distributions (mean, sorting and skewness) of the material sampled along the path of examined sediment transport. Unidirectional sediment transport can be

Table 1 Sampling periods and weather conditions during and shortly before the sampling

Sampling periods	Wind during sampling	Previous periods of windy weather, wind direction, speed, duration	
Russian part: 10-15.08.2011	SSW, SW, WSW, W, 1-5 m/s	09-10.08.2011	WSW, 8-11 m/s (gust 11-17 m/s), 48 hours
Russian part: 04-05.08.2014 Lithuanian part: 11-12.09.2014	ENE, E, SE, 2-3 m/s NE,E, SE, 1-3 m/s	01.05.2014 14.06.2014 19-21.08.2014 25.08.2014 27.08.2014	NW, 5 m/s (gust 10-13 m/s), 9 hours NW, 4-6 m/s (gust 8-11 m/s), 12 hours SSW, 6-8 m/s (gust 11-16 m/s), 39 hours WSW, 5-6 m/s (gust 10-13 m/s), 12 hours SSW, 5-6 m/s (gust 11-12 m/s), 6 hours + NW, 5-6 m/s (gust 11 m/s), 9 hours
Russian part: 22.06.2015	SE, SW, 1-3 m/s	09.06.2015 15.06.2015 18.06.2015	NW: 3-5 m/s (gust 6-11 m/s) 21 hours WSW, 3-4 m/s (gust 7-9 m/s), 21 hours SSW, 4-7 m/s (gust 9-14 m/s), 12hours

Table 2 Logarithmic method of moments (Krumbein, Pettijohn 1938), where m_φ is mid-point of each class interval in phi (*φ*) units, *f* is probability for each class interval, summation is given through all class intervals

Momentum	Physical meaning	Formula
1st	Mean grain size	$\overline{x}_\varphi = \dfrac{\sum f m_\varphi}{100}$
2nd	Standard deviation (or sorting)	$\sigma_\varphi = \sqrt{\dfrac{\sum f (m_\varphi - \overline{x}_\varphi)^2}{100}}$
3rd	Skewness of statistical distribution	$\sigma_\varphi = \dfrac{\sum f (m_\varphi - \overline{x}_\varphi)^3}{100\sigma_\varphi^3}$

Table 3 Types of sorting according to classification (Folk, Ward 1957)

Sorting	Standard deviation	Sorting	Standard deviation
Very well sorted	<0.35	Poorly sorted	1.00-2.00
Well sorted	0.35-0.50	Very poorly sorted	2.00-4.00
Moderately well sorted	0.50-0.70	Extremely poorly sorted	>4.00
Moderately sorted	0.70-1.00		

supposed in two cases: case 1 – sediments on the bottom along the transport flow become finer, sorting becomes more refined and skewness shifts toward more negative values; and case 2 – sediments become coarser, sorting becomes more refined, skewness shifts toward more positive values. Both cases could be attributed to real physical situations when an unidirectional water flow spreads over the plain of not cohesive free sediments: case 1 – an initial water flow fully saturated by sediments of various grain size slows down and loses fine-grade sediments; case 2 – speed of the water flow running over the unsorted sediments becomes faster and faster, and therefore the flux is 'fed' with fine sediments.

According to the authors' recommendation (McLaren, Bowles 1985), the aforementioned trends corresponding to cases 1 or 2 should be analysed and taken into account for any pair in 8–9 sequentially collected samples of sediments. The level of significance shall be defined by *Z*-score:

$$Z = (x\text{-}N{\cdot}p)/(N{\cdot}p{\cdot}q)^{1/2},$$

where N – total number of possible unidirectional pairs, $N = (n^2{-}n)/2$, n – number of samples in sequence, x – number of pairs matching with described trends, p – probability of sediment transport of the analyzed direction, $p = 0.125$, $q = 1{-}p = 0.875$.

If ($2.33 < Z$), the level of significance is equal to 0.01 and examined direction is quantitatively classified as 'very probable'. If ($1.645 < Z < 2.33$), the level of significance is equal to 0.05 and examined direction is classified as 'probable'. If ($Z < 1.645$), the level of significance is not determined and examined direction is classified as 'improbable'.

The method was applied in two modes: (a) for the whole set of sampling points for each field campaign; and (b) in a "running window" mode. In case of the latter, we screened a set of sampling points by "running window" of nine points and calculated the level of significance (*Z)* for each 'window' making conclusion about quantitative characteristics of transport existence and direction. If the first mode is an integral approach for the whole shore segment explored, the second mode is actually a 'differential' approach considering that transport direction may change within the shore segment explored.

Since in case (b) any point was involved in 9 'windows', in respect of which a conclusion about transport may vary, therefore a conventional indicator (WI) was introduced for each 'window': 1 – flux is 'very probable', 0.5 – flux is 'probable', 0 – flux is 'improbable'. As we analysed pairs of sampling points in the south-to-north order, the indicator value was assigned as positive for northward transport, and the negative one was attributed for southward transport. The accumulative point-wise value of conventional indicator (possible maximum is 9) was assumed as a sum of window-wise values of conventional indicator ($CI=\Sigma WI_{k.}$, k=1,9). This accumulative point-wise value of conventional indicator is actually the measure of confidence, which shows the reliability of conclusion about the unidirectional flow at the given point. Hereinafter the term 'confidence indicator' will be used to refer to this accumulative point-wise value. The value and sign of 'confidence indicator' will indicate both the measure for unidirectional flow to exist at the given point and the direction of this flow.

Estimation of cross-shore sediment movement according to 'McLaren' method

Principles of 'McLaren' method could be used not only in respect of long-shore sediment transport determination but for describing of cross-shore sediment transport as well (McLaren 1981). Changes in grain-size parameters of two samples of deposits can give an answer to the question "Can sediments at one point be a source for sediments at another point?" It is argued in (McLaren 1981; Maeyer, Wartel 1988) that if an area is supposed to be a sediment source, there are two choices for any second point existing on the way of sediment. The first variant is down to the assumption that this point is a point of final sedimentation of transport flow which has lost some sediments on the way. As we accept a greater probability of coarse grains to be deposited from sediment flow than fine grains as an assumption, the finally deposited sediment is finer, better sorted and more negatively skewed in this case than the source. Other variant outlines selective deposition of sediment due to decreasing energy of transportation process (sedimentation on the way of transport flow). The deposit grain-size compared to the source one can be coarser (if transportation process involves a flow and more coarse grains than mean-sized grains) or finer (if only finer mean-sized grains are involved in transportation process). In both cases final deposits are better sorted and more positively skewed. What happened to source sediments with the course of time or to deposited sediments due to secondary erosion? The sediment undergoes erosion and the remaining deposit (lag) is coarser, better sorted and more positively skewed than the source one. As a beach slope and underwater face are dynamic systems, selective deposition of sediment is a more likely process than total deposition.

RESULTS

Grain size distribution along the shore

Most of the samples collected in 2011 on the Russian side of the spit showed that upper layer sediments at the shoreline were composed of medium well sorted sand (Fig. 3a). It was confirmed by sampling in 2015; only three sediment samples out of nine collected were recognized as coarse sand, others were composed of medium sand.

The mean diameter of sediment samples collected in 2014 along the whole length of the spit had wider range of variability: 75% of samples corresponded to medium sand, 13% of samples to coarse and 12% to fine sand. With increase of the distance from Zelenogradsk (0 at the distance axis), mean grain size of shoreline deposits gradually changed from course to finer sand (2–2.5 φ). Mean grain size remains relatively the same with some variations along the Russian half of the spit with a trend to finer sediments towards the end of the Lithuanian side. This trend was also well-distinguished in terms of changes of mean deposit diameter of the middle and upper part of the beach (Fig. 3b). A segment of the shore (about 65–80 km, Pervalka and Juodkrantė, i.e., between the 66th and 88th per cent of the spit length) was found where the amplitude of alongshore variations of mean grain size increased significantly, shoreline deposits were represented not only by medium and fine sand but coarse sand as well there. Details of this lithological anomaly were analysed in the paper (Jarmalavičius *et al.* 2015).

In 2014, samples were collected at the shoreline, middle and upper parts of the beach (273 samples in total). It was found out that mean diameter, sorting, and skewness of the sediment samples collected at each transect on the southern half of the spit (42 ones) were nearly uniform; whereas on the northern half of the spit alongshore variations of these parameters (not only at the shoreline deposits but at the middle and upper parts of the beach) became wider towards the northern end of the spit.

The sorting of beach samples (Fig. 3c) varies between well-sorted and very well-sorted with certain cases of moderately sorted sediments actually for the whole spit. The variability of sorting was very high (from well-sorted to poorly sorted) at the same shore segment where the increase in variations of mean grain size was found.

The similar situation was essentially observed with skewness (Fig. 3d). Skewness of beach sediments of the southern and middle parts of the spit varies within a narrow range of negative values. Skewness of sediments of the northern part of the spit changes significantly but negative values are still prevalent.

Estimation of long-shore sediment transport using the whole set of samples

As middle and upper parts of the beach mostly reflect eolian transport processes, here we shall discuss only samples of the shoreline affected by transport processes in the water. Data of 2011, 2014 and 2015-years covered different segments of the coastline so it was important to compare them first. The 'McLaren' method (identification of cases 1 and 2) was applied first to the whole set of the samples collected within one field campaign (Table 4). The long-shore sediment transport for 2011 and 2014 was estimated according to opposite directions (northward in 2011 and southward in 2014, Fig. 4) with the highest level of significance. In 2015, the 'McLaren' method detected only northward direction with a low level of significance.

The principle scheme of the bulk alongshore sediment transport direction regardless the detailed distribution of the alongshore sediment transport rate on the cross-shore profile is presented in Fig. 4. The results of the study (Ostrowski, Szmytkiewicz 2006) showed that alongshore sediment transport is concentrated in relatively narrow zones near the major wave breakers, such as underwater bars, where waves were accompanied by a strong alongshore flow.

Estimation of long-shore sediment transport using 'running window' approach

Application of 'McLaren' method for running '9-point window' for 2011 (the coastal segment Zelenogradsk – Rybachy) revealed four sections of the shoreline (Fig. 5a) where long-shore sediment transport could be characterised by 1.5–5.5 values of 'confidence indicator'. Changes of the sediment transport directions may mark zones of flux convergence and divergence, i.e. material accumulation or erosion, but we didn't find any such manifestations on the shore surface and its morphology at the moment of sampling.

When applying the same method for data of 2014-year, we didn't reveal the same structure of sediment transport directions as it had been in 2011. For the central part (38–78 km) of the spit the method showed possible sediment transport directed southward but at the northern (80–94 km) and southern parts (22–35 km) of the spit the flux was identified as directed northward (Fig. 5b). Sediment fluxes at the segment near Rybachy and Nida were characterised by a rather

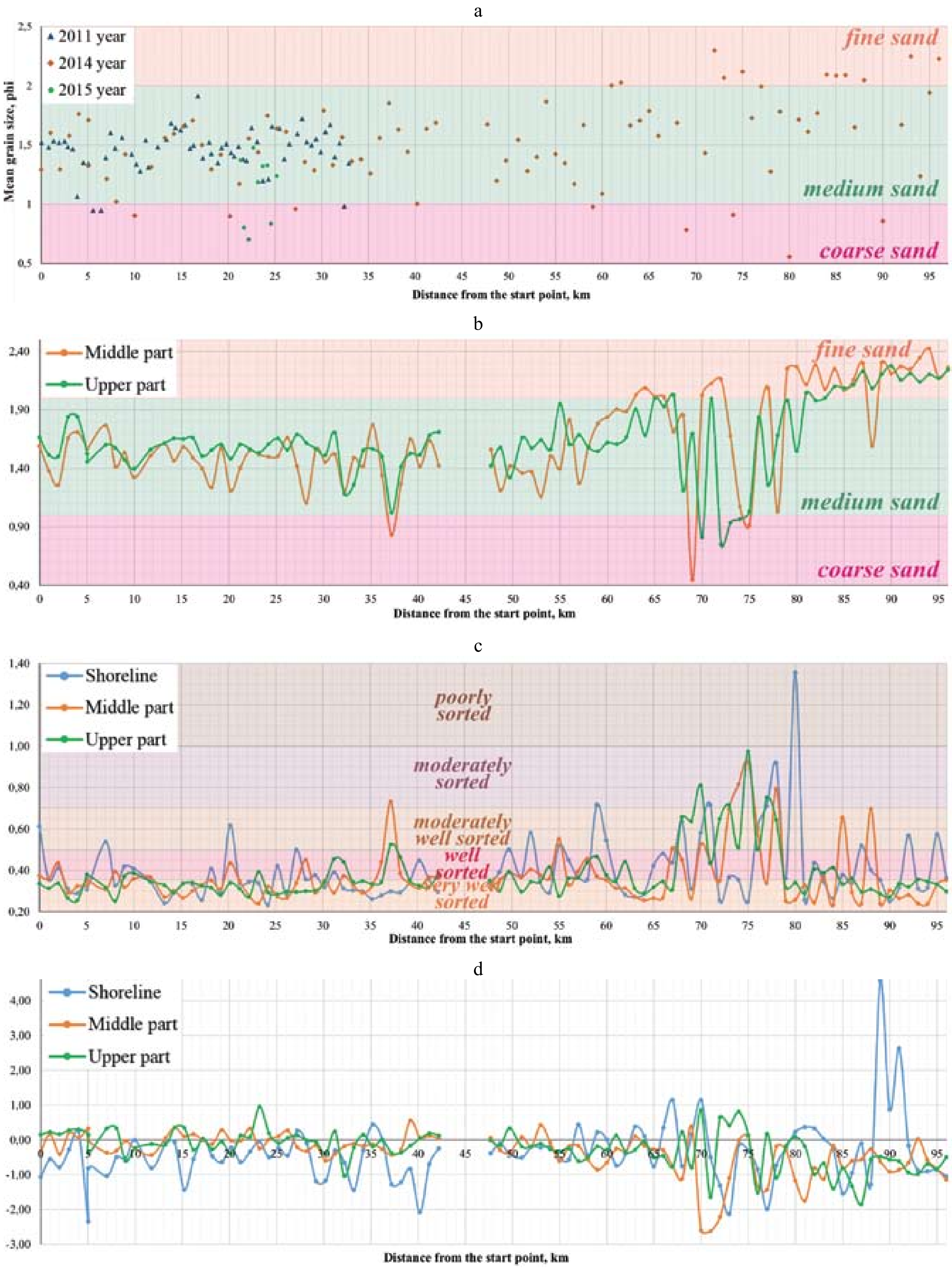

Fig. 3 Alongshore variations of grain size characteristics for the samples collected along the Curonian Spit shore: mean size (in φ units) for (a) shoreline (all three years 2011, 2014 and 2015) and (b) beach sediments (middle and upper parts, 2014), (c) sorting (2014), and (d) skewness (2014). Compiled by O. Kovaleva, 2015

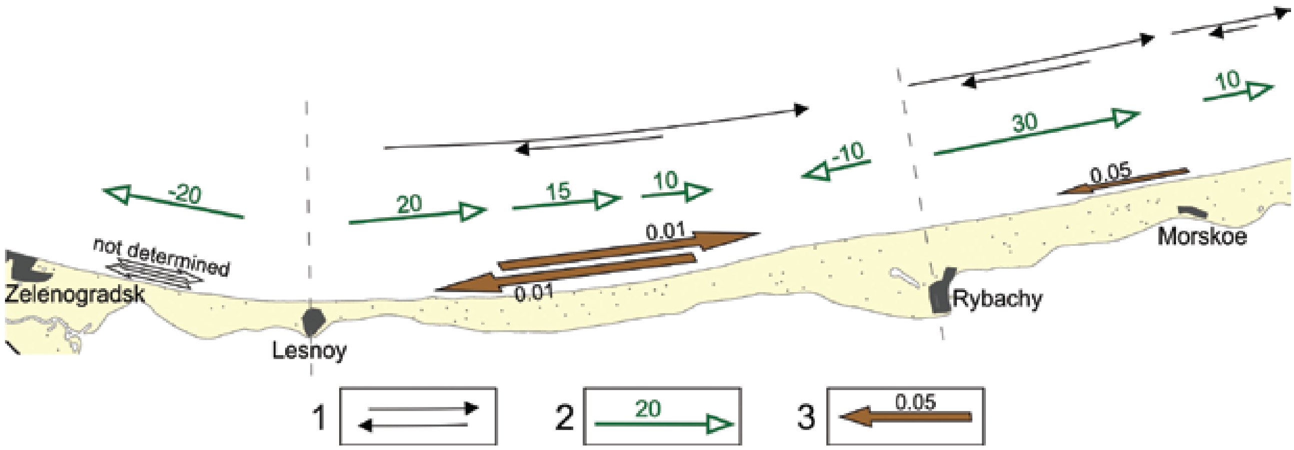

Fig. 4 Comparison of directions of long-shore sediment transport determined by different approach: 1 – relative value of sediment transportation strength directed northward and southward described by (Gudelis *at al.* 1977); 2 – resultant sediment fluxes (m^3/year) and their directions calculated by (Leont'ev, Akivis 2014); 3 – directions and significance levels of long-shore sediment transport estimated by 'McLaren' method in this study using data of 2014. Compiled by O. Kovaleva, 2015

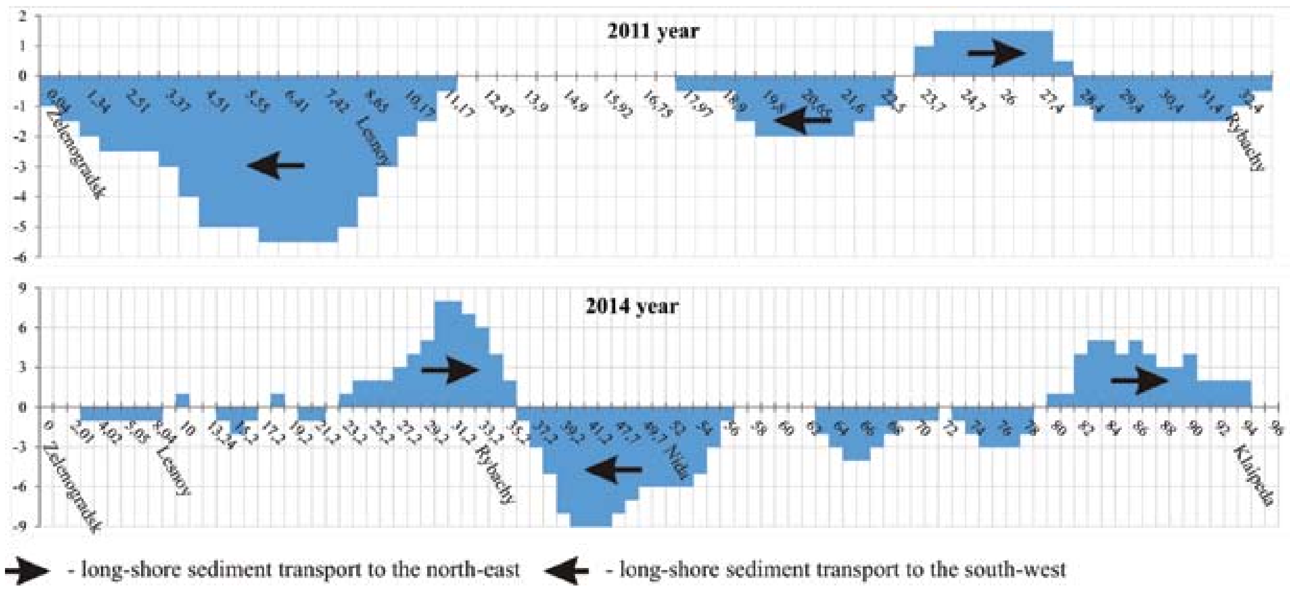

Fig. 5 The level of confidence ('confidence indicator', dimensionless) and direction of long-shore sediment transport for the seashore of the Curonian Spit based on application of the ''McLaren' method': (a) 2011, (b) 2014, axis X shows the distance (in kilometres) from Zelenogradsk. O. Kovaleva, 2015

Table 4 Estimated level of significance for tested directions of the long-shore sediment transport using grain-size distributions for the whole sets of samples obtained in 2011, 2014 and 2015

Tested direction	*x*		*Z*		Level of significance	
	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
2011						
Northward	320	294	5.81	4.01	0.01	0.01
Southward	302	256	4.56	1.57	0.01	Not defined
2014						
Northward	842	468	15.6	-2.07	0.01	Not defined
Southward	714	767	9.55	12.05	0.01	0.01
2015						
Northward	7	8	1.26	1.76	Not defined	0.05
Southward	3	6	-0.76	0.76	Not defined	Not defined

high level of 'confidence indicator' (up to the maximum value) and were opposite directed, indicating a local point of divergence.

Analysis of cross-shore sediment transport

45 samples were collected on the 22nd of July 2015 at nine cross-shore transects, five samples per transect located at the last underwater bar (1 m deep), the trough between this bar and shoreline (about 1.5 m deep), the shoreline, middle part of the beach, upper part of the beach. The coarsest material was detected on the shoreline; sand on the underwater bar and the upper part of the beach was the finest and characterized by the highest values of mean grain size (up to 2.11 in φ units) (Fig. 6). Almost all samples showed that sand was well or very well sorted. It is interesting that shore face and berm are composed of material with better sorting than the one of the trough and the bar.

Sediment trend matrix (McLaren 1981) was compiled for determination of sediment travelling paths. It compares each pair of samples related to one particular profile (example is provided in Table 5).

DISCUSSION

Estimation of long-shore sediment transport using the whole set of samples

To compare the views on sediment transport presented in (Gudelis *et al.* 1977; Leont'ev, Akivis 2014) with results of application of 'McLaren' method, the samples from the Russian part of the Curonian Spit taken in 2011 and 2014 were divided into three sub-

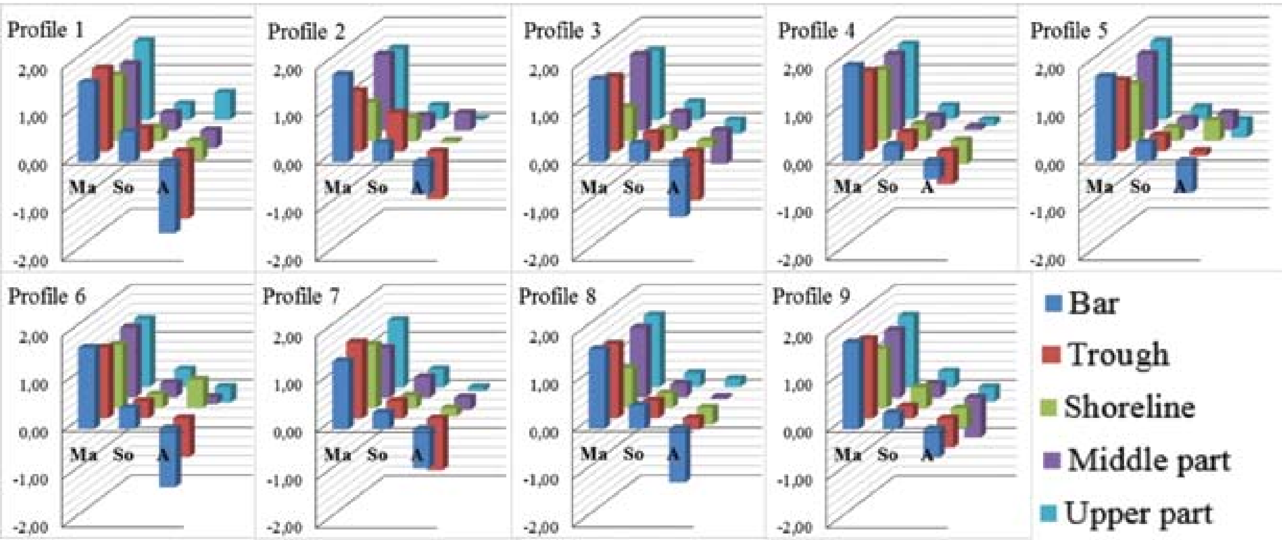

Fig. 6 Grain-size parameters, namely mean grain size (Mn), sorting (So) and skewness (A) of sand samples collected at cross-shore transects in 2015. Compiled by O. Kovaleva, 2015

Table 5 Example of the sediment trend matrix made for samples collected at the most northern transect in 2015. The matrix gives a frame to test the hypothesis that each two samples form a 'source-deposit' pair. Each cell contains characteristics of sediments: whether the 'deposited' sediment is coarser or finer, better or poorer sorted, more positive (+) or more negative (-) skewed than 'source' sediments

		Deposits					
		Upper part	Middle part	Shoreline	Trough	Bar	
Sources	Upper part		Coarser Poorer –	Coarser Better –	Finer Poorer –	Finer Poorer –	*Mean* *Sorting* *Skewness*
	Middle part	Finer Better –		Coarser Better –	Finer Poorer –	Finer Poorer –	*Mean* *Sorting* *Skewness*
	Shoreline	Finer Poorer +	Finer Poorer +		Finer Poorer –	Finer Poorer –	*Mean* *Sorting* *Skewness*
	Trough	Coarser Better +	Coarser Better +	Coarser Better +		Coarser Poorer –	*Mean* *Sorting* *Skewness*
	Bar	Coarser Better +	Coarser Better +	Coarser Better +	Finer Better +		Mean Sorting Skewness

sets according to the shore segments. For the first segment (Zelenogradsk–Lesnoy), 'McLaren' method did not reveal sediment transport with a sufficient level of significance, but the method considering waves impact (Leont'ev, Akivis 2014) outlined a possible point of divergence of resultant sediment fluxes at Lesnoy. At the next shore segment (Lesnoy–Rybachy), 'McLaren' method showed northward and southward sediment transport (with a high level of significance 0.01) for 2011 and 2014-years respectively. According to (Gudelis *et al.* 1977; Leont'ev, Akivis 2014), the sediment transportation strength of northward flux at this segment is higher than southward, and there is a divergent point (Leont'ev, Akivis 2014) within this coastal segment. At the last segment (Rybachy–Morskoye), 'McLaren' method showed southward sediment transport with a low level of significance 0.05, while the dominance of northward transportation was detected there (Gudelis *et al.* 1977) and proved by numerical modeling (Leont'ev, Akivis 2014).

The above comparison has showed that 'McLaren' method is very unlikely to reveal long-term resultant sediment transport on the basis of the whole set of samples obtained at one given moment.

Estimation of long-shore sediment transport using 'running window' approach

Results of application of 'McLaren' method to the data of 2011 and 2014-years did not coincide. The shore segment (3–9 km) which was characterized in 2011 by unidirectional northward flow of rather high grade of confidence ('confidence indicator' was higher than 3) was not revealed in the data of 2014-year. On the contrary, the divergence point of Rybachy and Nida formed by two opposite directed flows, which was confidentially revealed in the data of 2014 ('confidence indicator' was up to its possible maximum) was not distinguished at all in the data of 2011-year.

As all samples of 2011 and 2014-years were collected under relatively calm weather conditions, the second hypothesis was that 'McLaren' method probably indicated the direction of the sediment transport existing during stormy conditions shortly before the sampling. Fortunately, weather conditions in 2011 and 2014 were similar and might predestine the same pattern of sediment transport. Though, as shown in Fig. 6, the direction of sediment transport resulted from 'McLaren' method was different in each analysed period. Therefore, we may conclude that variations of lithodynamic characteristics considered by 'McLaren' method most probably do not reflect the sediment transport prevailing during aforegoing storm event.

Taking into account the positive results of 'McLaren' method use cited above (McLaren, Bowles 1985; McLaren 1981; Mohd-Lokman *et al.* 1998; Wu, Shen 1999), we may suppose that its application to the elongated straighten shore of the Curonian Spit was not successful due to the transit nature of the shore and lack of such important factors as river inflow or bays, or capes which may predominantly determine the directions of sediment transport. Therefore the resultant sediment transport along the Curonian Spit should be determined preferably via traditional methods taking into account wind and waves parameters as well as final geomorphological features.

Analysis of cross-shore sediment transport

Since the sampling in 2015 was carried out after the one month period of calm weather, it was decided to test the hypothesis that sediment transport during this period had happened according to general understanding of evolution of a sandy spit under calm weather conditions (Fig. 7). We aimed to approve using the principles of 'McLaren' method that the sand transported alongshore in the water was a source of material for the beach and further for the foredune.

Using sediment trend matrixes for all transects, the directions of sediment movement at each couple of geomorphological structures (bar, trough, shoreline, middle and upper beach) were tested for each particular transect (Table 6). It appeared that there is no equal picture of cross-shore transport for all tested transects; results shows variations for all tested direc-

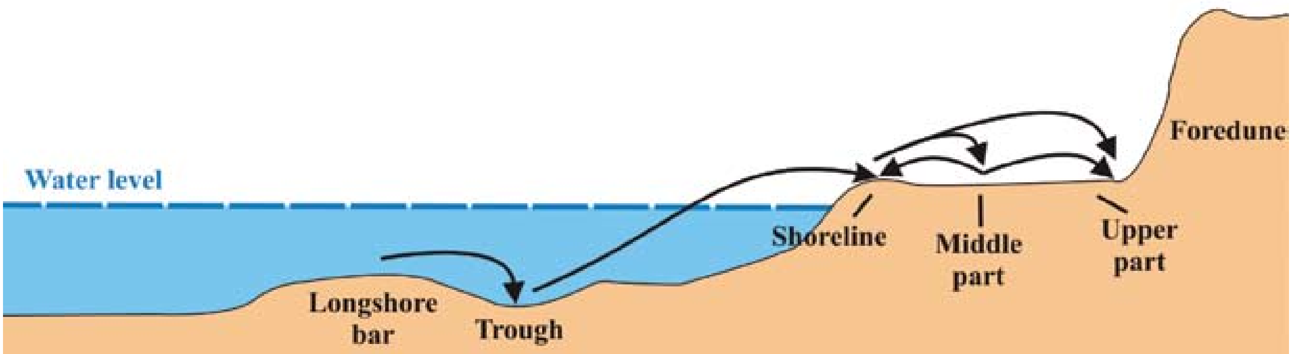

Fig. 7 Pattern of possible directions of cross-shore sediment transport tested by analysis of grain-size distribution for all cross-shore transects in 2015. Compiled by O. Kovaleva, 2015

Table 6 Testing the direction of cross-shore transport by the samples taken on the 22nd June, 2015

Transport direction (from→to)	Transects									Is it confirmed for the majority of profiles?
	1	2	3	4	5	6	7	8	9	
Bar→trough	-	-	+	-	+	+	-	+	-	50% - 50%
Trough→shoreline	+	+	+	+	+	+	+	-	-	Yes
Shoreline→middle beach	-	-	-	-	+	-	-	-	+	No
Middle beach→upper beach	+	-	+	-	-	-	-	-	-	No
Shoreline→upper beach	-	-	-	-	+	-	-	-	-	No

tions of sediment transport. The transport of the material from alongshore underwater bar to the trough between the bar and shoreline was evident for a half of the transects. The fact of upslope transport from the trough (located between the bar and shoreline) to the shoreline was evident for majority of transects, and it seems in a line with general understanding about onshore transport of bottom material during the calm weather and results already obtained for some coastal segments at the Curonian Spit (Jarmalavičius, Žilinskas 2006). 'McLaren' method revealed transport from the shoreline upward the middle and upper part of the beach for only few transects, and therefore such transport directions couldn't be common for that part of the Curonian Spit.

CONCLUSIONS

Deposits of the shoreline of the Curonian Spit, as well as middle and upper parts of the beach consist of medium well-sorted sand according to data of 2014-year (as well as of 2011-year in the southern part of the spit). Mean grain size remains relatively the same with some variations along the southern (Russian) half of the spit with a trend to finer sediments towards the end of its northern (Lithuanian) side. There is a segment of the shore between Pervalka and Juodkrantė (i.e. between the 66th and 88th per cent of the spit length) where variations of mean grain size and sorting were considerably higher than on another shore of the Curonian Spit. Variations of grain-size parameters (mean grain size, sorting and skewness) generally increase from south to north along the Curonian Spit marine shore.

Directions of sediment transport estimated by 'McLaren' method using data of 2011 and 2014-years did not coincide. Possible local point of divergence confidentially revealed in 2014 was not found in the data of 2011-year. Considering that weather conditions shortly before and during the sampling were similar in 2011 and 2014, we may make a negative conclusion about the hypothesis that 'McLaren' method indicates the sediment transport direction under stormy conditions preceding the sampling period shortly before the sampling.

The sediment transport pattern composed according to 'McLaren' method based on data of 2014-year (the whole spit area was subjected to sampling) did not coincide with those obtained by the methods based on existing geomorphological study (Gudelis *et al.* 1977) and simulations of generated wave action (Leont'ev, Akivis 2014). Therefore the hypothesis that 'McLaren' method is able to reveal long-term generated sediment transport was not proved.

The application of 'McLaren' method in respect to the shore without permanent sources or sinks of sediments (river inflow, bays, capes) is not efficient; determination of sediment transport along the Curonian Spit shore, which is generally transit, should be carried out through methods based on wind and wave influence.

'McLaren' method may be most probably used for small shore segments; at least we found out that its application to cross-shore sediment distribution had shown the onshore transport of deposits from the trough (located between the bar and shoreline) to the shoreline, so that it seems in a line with general understanding about onshore transport of bottom material during the calm weather.

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