Morphological and lithodynamic conditions in the marine coastal zone of the Vistula Spit (Gulf of Gdańsk, Baltic Sea)*

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Abstract

The paper presents a lithodynamic interpretation of the Polish-Russian morphological and lithological research project along the marine coastal zone of the Vistula Spit, carried out between July and September 2008. 78.4% of the coastal zone is characterized by a balanced environment, with fractional transport of sediments as bed and suspended load. Deposition was observed in 8.2% of the study area. A dynamic environment with a deficit of bed material, local turbulences and erosive trends were found in 13.2% of the coastal zone. The critical erosive current velocities vary from 16 to 20–26 cm s^{-1}.

1. Introduction

The Vistula Spit's marine coastal zone is a complex and changeable morpho-lithodynamic system. The main sources of bed load for the study area are the Vistula River mouth (0.4–1.4×10^6 t per year), the Sambian Peninsula (22×10^3 m^3 per year from the western coast and 1.5×10^6 m^3 per year from the northern coast), the eroded Vistula palaeodelta, and abrasive platforms located in the Gulf of Gdańsk (Passchier et al. 1997, Ryabkova 2002).

Earlier studies conducted in the Vistula Spit provided important information about coastal processes (Musielak 1980, Rosa & Wypych 1980, Solovieva & Badiukova 1997, Zawadzka-Kahlau 1999, Boldyrev & Bobykina 2001, Babakov 2008, Chechko et al. 2008, Bobykina & Karmanov 2009). These studies, however, focused mostly on certain western or eastern stretches of the coast. Particularly with respect to the lithological studies, the time and methodology of the research differed significantly. As a result, comparison of these studies is difficult, and the questions of morphometric structure and lithodynamic conditions still need to be addressed.

The study presented in this paper includes the results of transborder morphological and lithological onshore and nearshore research, performed by unified methods in cooperation between the Department of Marine Geology, Institute of Oceanography, University of Gdańsk (Gdynia, Poland) and the Laboratory of Coastal Systems, Atlantic Department of the P. P. Shirshov Institute of Oceanology of the Russian Academy of Sciences (RAS) (Kaliningrad, Russia) (Bobykina et al. 2009). A lithodynamic interpretation of the collected data was carried out, and two different methods of shore sediment sampling were compared.

1.1. Study area

Separating the Vistula Lagoon from the Gulf of Gdańsk, the Vistula Spit is a Holocene accumulative form located in the southern Baltic (Figure 1).

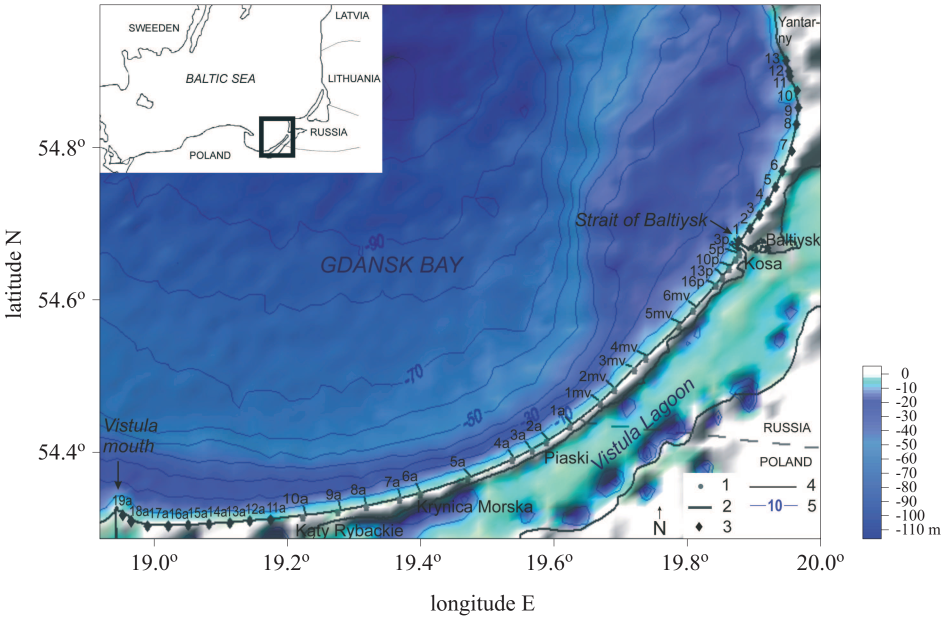

Figure 1. The study area in July–September 2008: 1 – shore cross-profiles with surficial sediment sampling, 2 – nearshore cross-profiles with surficial sediment sampling, 3 – sampling of shore surficial sediment, 4 – coastline, 5 – isobaths (the geographical coordinates x, y, z of the map are taken from Smith & Sandwell 1997)

The Spit shore consists of a foredune (white dune) and a beach with locally occurring berm ridges and lagoons. The above-water Holocene dune ridges are built of wind-transformed marine sands (Tomczak 1995, Badiukova et al. 1996, Solovieva & Badiukova 1997). The shallow marine nearshore, the surf zone, is represented by accumulative landforms such as shoals and longshore bars.

The research area included two study sections: 1. the 55 km long stretch from the Strait of Baltiysk in the east to the village of Kąty Rybackie in the west was the object of comprehensive morphological and lithological research (Figure 1); 2. the two adjoining stretches – from Yantarny to the Strait of Baltiysk (Sambian Peninsula) and from Kąty Rybackie to the Vistula mouth (the western end of the Vistula Spit) – were studied with respect to coastal lithology only (Figure 1).

2. Material and methods

The investigations involved the construction of shore and nearshore cross-profiles, grain-size analysis by dry sieving, and a lithodynamic interpretation of the results.

2.1. Topographic and bathymetric measurements

21 shore cross-profiles of the beach and the foredune were linked to a fixed geodetic benchmark: they were generated by a theodolite (3T5PK) in the eastern part, and by a tachymeter (TTS-500 Trimble) in the western part of the study area (Figure 1).

21 nearshore cross-profiles constituted the marine continuation of the coastal profiles, and were generated by an echo sounder (GPS Garmin 168 Sounder) in the eastern part of the Spit and a NAV net vx2 c-map NT MAX Foruno in the western part, with a 200 kHz signal (Figure 1). The acoustic devices were calibrated before the measurements were made. The maximum vertical error was calculated at 0.3 m, owing to the technical specifications and hydro-meteorological conditions during the research. The minimum depth of the nearshore cross-profiles was dependent on the draught of the ships: it was 0.8–1 m in the western stretch and 2–5 m in the eastern part. The maximum depth was delimited by the 10 m isobath.

The topographic and bathymetric data were interpolated by kriging in Golden Software Surfer 8.0.

During the measurements, the average speed of SW-NW winds (72.9%) was 5 m s^{-1} and the average sea level was 509 cm, according to the data supplied by the ARMAAG Foundation and Ecohydrodynamic Model of Institute of Oceanography, University of Gdańsk (Kowalewski 2002).

2.2. Sediment analysis

The samples of surficial sediment were collected from the whole width of the beach according to the methodology used by the P. P. Shirshov Institute of Oceanology, RAS, and separately from the shore morphological forms: 30 cm depth (shallow nearshore), the waterline, a berm (if present), the centre and the upper part of the beach (the base of the foredune) (Figure 2).

On the south-western (Polish) part of the Spit, nearshore sediment was collected from all bars and troughs. Along the north-eastern (Russian) part, samples were collected from depths of 5–1 m, regardless of morphology. The deeper nearshore sampling points were located at depths of 7 m and 10 m (Figure 2).

The paper includes the results of the grain-size analysis of 263 samples by dry sieving in an Eko-Lab analyser with 0.5 φ mesh sieves (from 4 to 0.004 mm). The lithodynamic indices – mean (M_G), sorting (σ_G), skewness (Sk_G) and kurtosis (K_G) – were calculated using the method of Folk & Ward (1957), which is the most accurate for sandy deposits in the marine coastal zone (Racinowski et al. 2001) (Tables 1 and 2). Grain-size values were calculated with the Gradistat program (Blott & Pye 2001).

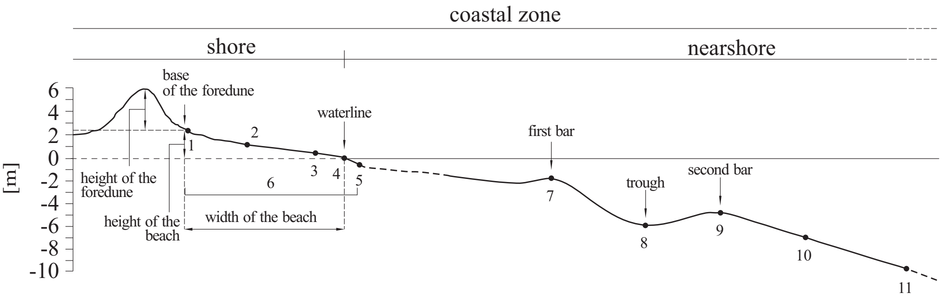

Figure 2. Sampling locations along the shore and nearshore cross-profiles: 1 – the base of the foredune, 2 – the centre of the beach, 3 – a berm, 4 – the waterline, 5 – 30 cm depth, 6 – samples collected from the whole width of the beach along a cross-profile (according to the methodology of the P. P. Shirshov Institute of Oceanology, RAS), 7–9 – longshore bars and troughs in the western part of the spit and 5–0.9 m depth in the eastern part, 10 – 7 m depth, 11 – 10 m depth

Table 1. Grain-size indices calculated by Folk & Ward's method (1957): mean (M_G), sorting (σ_G), skewness (Sk_G) and kurtosis (K_G). P_x – grain diameters in mm, subscript x – cumulative percentile value. Sorting (σ_G): < 1.27 very well sorted, 1.27–1.41 well sorted, 1.41–1.62 moderately well sorted, 1.62–2.00 moderately sorted, 2.00–4.00 poorly sorted, 4.00–16.00 very poorly sorted, > 16.00 extremely poorly sorted; Skewness (Sk_G): -0.3 to -1.0 very finely skewed, -0.1 to -0.3 finely skewed, -0.1 to $+0.1$ symmetrical, $+0.1$ to $+0.3$ coarsely skewed, $+0.3$ to $+1.0$ very coarsely skewed; Kurtosis (K_G): < 0.67 very platykurtic, 0.67–0.90 platykurtic, 0.90–1.11 mesokurtic, 1.11–1.50 leptokurtic, 1.50–3.00 very leptokurtic, > 3.00 extremely leptokurtic

Mean	Sorting
$M_G = \exp \frac{\ln P_{16} + \ln P_{50} + \ln P_{84}}{3}$	$\sigma_G = \exp\left(\frac{\ln P_{16} - \ln P_{84}}{4} + \frac{\ln P_5 - \ln P_{95}}{6.6}\right)$
Skewness	**Kurtosis**
$Sk_G = \frac{\ln P_{16} + \ln P_{84} - 2(\ln P_{50})}{2(\ln P_{84} - \ln P_{16})} + \frac{\ln P_5 + \ln P_{95} - 2(\ln P_{50})}{2(\ln P_{25} - \ln P_5)}$	$K_G = \frac{\ln P_5 - \ln P_{95}}{2.44(\ln P_{25} - \ln P_{75})}$

The lithodynamic interpretation of all grain-size indices was done on the basis of the confidence interval calculated for the standard deviation of the mean (M_G), sorting (σ_G), skewness (Sk_G) and kurtosis (K_G), with

Table 2. Grain-size classification of sandy sediments (Wentworth 1922)

Grain size		Description	
phi	mm		
−1	2		gravel
		very coarse	
0	1		
		coarse	
1	0.5		
		medium	sand
2	0.250		
		fine	
3	0.125		
		very fine	
4	0.063		silt

the confidence level of 90%. Passega C/M (1964) and Hjulström (1935) diagrams were constructed. The comparison was carried out on the mean (M_G) and sorting (σ_G) of the samples collected from the shore by two different methods (Figure 2). Lithological data were interpolated by kriging in Golden Software Surfer 8.0.

3. Results

3.1. Morphology

The shore zone of the Vistula Spit consists of one or two (profiles 16p, 5mv, 3mv, 3a, 8a, 9a, 10a) foredunes developed to various degrees (Figure 3).

In the north-eastern part of the Vistula Spit, on the 400 m long shore adjacent to the Strait of Baltiysk, there are no foredunes owing to intensive erosion. In the south-western part of the Spit, the shore is represented by older, afforested dunes, with a relative height of 5.1–14 m (profiles 6a–10a, Figure 3). In the remaining area, between profiles 5p and 6a, the relative height of the foredune ranges between 4 and 9 m (Figure 3).

At the base of the foredune, the 1–3.5 m high initial dunes are formed locally (profiles 16p, 5mv, 3mv, 3a, 8a–10a).

The slope of the foredune is 3° near the Strait of Baltiysk (profile 3p), 9.5°–13° on profiles 6mv, 5mv and 5a, and 24–30° on profiles 10p and 7a.

The beach along the Vistula Spit is from 10 m (profile 3p) to 43–45 m (profiles 1mv, 6a) wide and from 1 m (profile 3p) to 3 m (profiles 5p–13p, 1mv, 10a) high. The slope of the beach is from 2.7°–2.9° (profiles 3mv, 4mv, 6a) to 6.4°–6.7° (profiles 13p, 9a).

The system of one (profiles 1a–2a and 7a–10a) or two longshore bars is located in the nearshore (Figure 3). One longshore bar with a height from 0.3 m (profile 10p) to 2.6 m (profiles 13p and 1a) is separated from

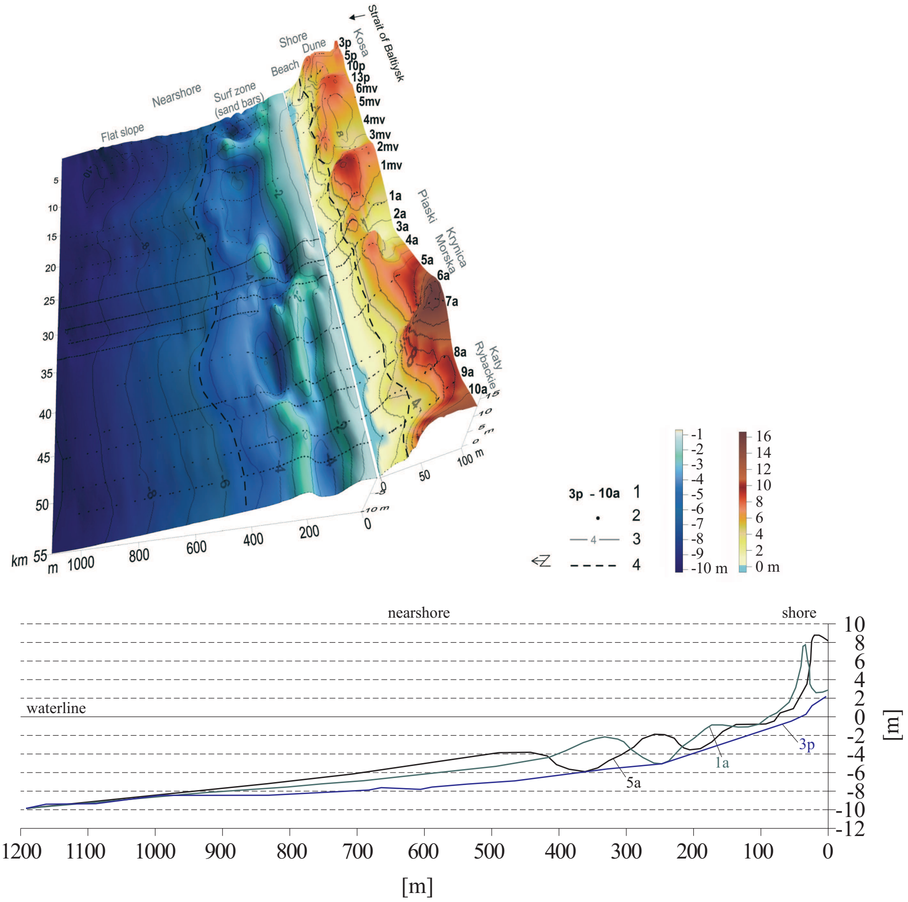

Figure 3. Morphology of the marine coastal zone of the Vistula Spit. 1 – location of cross-profiles; 2 – measuring points; 3 – isobaths and contour lines; 4 – the border between the zone with longshore bars (surf zone) and the flat nearshore slope, and between the beach and the foredune

the shore by a trough located 80–100 m from the shoreline, at depths of 3.5–4.8 m (Figure 3). In the nearshore with two 0.5–1.9 m high bars, the trough separating the first bar from the shoreline is located closer to the shore (10–70 m), at depths of 2.2–3.4 m (profiles 3a–6a, Figure 3). The 3.6–5.7 m deep trough that separates the first and the second longshore bar is located 173–280 m from the shoreline (Figure 3).

On the north-eastern part of the Vistula Spit, determination of the number of longshore bars was difficult owing to the greater 'starting depth' of the nearshore cross-profiles. Along that area there was one bar (Figure 3) located 210–240 m from the shoreline and separated by a 4–7.1 m deep trough. Near the Strait of Baltiysk, on profiles 3p and 5p with respective 'starting depths' of 2.8 and 2.6 m, there are no accumulative forms in the nearshore (Figure 3).

The longshore bars are mainly asymmetrical, with steeper shore-oriented slopes – 0.4°–2° (profiles 4mv, 8a, 13p) – or with steeper seaward slopes – 0.7°–2.3° (profiles 16p, 6mv, 1mv, 3a). The only bars located on profiles 1a, 4mv and 5mv are nearly symmetrical.

The nearshore zone with bars, the surf zone, is inclined from 1.5° (profile 13p) to 2° (profiles 1a, 9a), and is delimited by depths of 5.3–6 m (Figure 3). The width of this zone varies from 330 m (profile 2a) to 575 m (profile 5mv). The nearshore slope behind the most seaward longshore bar is flattish and inclined at 0.1°–0.6°.

3.2. Granulometric framework

Grain-size analysis of the samples collected shows differentiation of sediment features along and across the coastal zone of the Vistula Spit. Across the shore, in the upper and middle part of the beach, fine and medium grained (0.24–0.5 mm), well sorted (1.25–1.39) sand is deposited (Figures 4a,4b). Only to the west of the village of Piaski (profiles 3a–4a, Figure 4b) is the sand moderately sorted (1.42–1.58).

Along the lower part of the beach and in the swash zone, the mean (M_G) is higher and sorting (σ_G) is worse (Figures 4a, 4b). Near the Strait of Baltiysk (profiles 3p–5mv) and near Piaski (profiles 2a–4a), the lower shore sediments are represented by moderately well, moderately, poorly, very poorly sorted (1.5–2.6), coarse, very coarse sand, and along the swash zone by gravel (0.8–4.0 mm) (Figures 4a, 4b). Between these stretches (profiles 4mv–1a) and to the south-west of profile 4a (profiles 5a–10a), in the lower part of the beach, the grain size decreases to medium (0.25–0.5 mm), well sorted (0.4–1.27) sand (Figures 4a, 4b).

The grain size differentiation in the surf zone (0.9–6 m depth) is strictly related to morphology. The mean (M_G) (0.18–1.46 mm) and sorting (σ_G) values (1.29–2.3) were higher in the trough between the longshore bars (profiles 1mv–10a; Figures 4a, 4b). The grain-size indices have the highest values in the trough near the village of Piaski: very poorly and poorly sorted (1.89–2.3) coarse sand and gravel (0.59–1.46 mm) (profiles 1a–3a, Figures 4a, 4b). In the north-eastern part of the Spit (profiles 3p–1mv) the sampling points were not related to the surf zone morphology. Greater grain size (0.25–0.4 mm) and sorting (1.3–1.6) were recorded at depths of 1–3 m between profiles 3p and 5mv (Figures 4a, 4b).

Along the flat nearshore slope, at depths of 10 and 7 m, the sediment consists mainly of fine grained (0.125–0.2 mm), moderately well (1.41

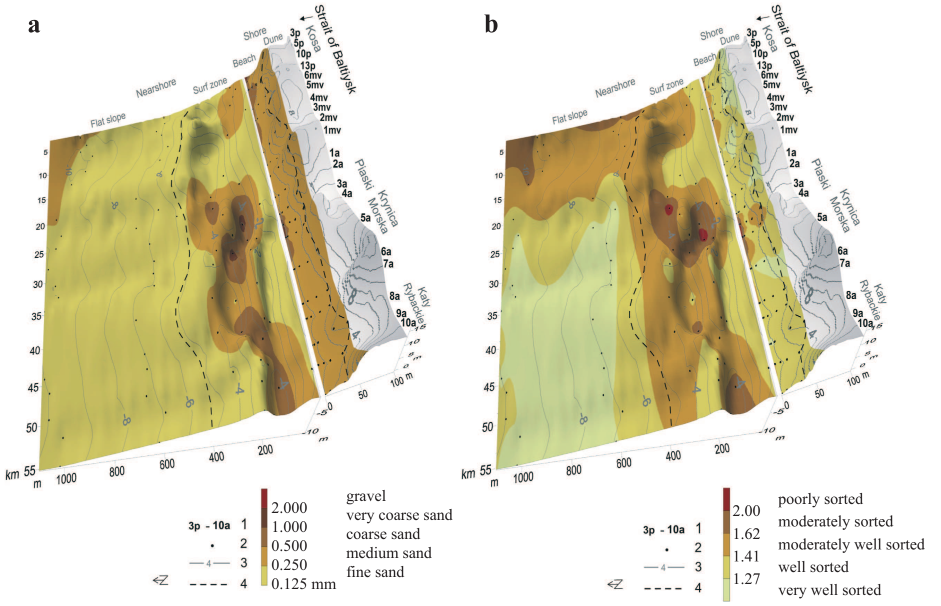

Figure 4. Grain-size indices: a) mean (M_G); b) sorting (σ_G) of the surficial sediment along the coastal zone of the Vistula Spit, calculated by Folk & Ward's method (1957). 1 – location of shore and nearshore cross profiles; 2 – sampling location; 3 – isobaths and contour lines; 4 – the border between morphological zones (surf zone and flat nearshore slope; beach and dunes)

–1.6) and well to very well sorted sand (1.22–1.33) (Figures 4a, 4b). Only the segment adjacent to the Strait of Baltiysk (profiles 3p–5p) consists of medium grained sand (0.25–0.49 mm), moderately sorted (1.6–1.9) (Figures 4a, 4b).

The grain size distribution curves are coarsely skewed on the shore stretches between profiles 6mv–3mv (0.1–0.21) and 2a–3a (0.11–0.2) (Figure 5a). Kurtosis (K_G) in these areas is leptokurtic (1.12–1.33) (Figure 5b). On the western part of the Spit (profiles 3a–10a) and near the Strait of Baltiysk (profiles 3p–10p) the shore sediment has symmetrical (0.1–0.9), mesokurtic (1.09–0.99) and platykurtic (0.88–0.76) grain size distribution curves (Figures 5a, 5b).

In the surf zone, coarsely and locally very coarsely skewed curves were obtained for stretches 1a–10a and 3p–5mv (Figure 5a). Kurtosis in this area is mesokurtic and leptokurtic (Figure 5b). In the deeper eastern and central part of the nearshore (10 m depth; profiles 3p–5a, Figures 5a, 5b), finely skewed, platykurtic and mesokurtic sediments are deposited. In the western part (profiles 5a–10a, Figures 5a, 5b), the grain size distribution curves are symmetrical and leptokurtic.

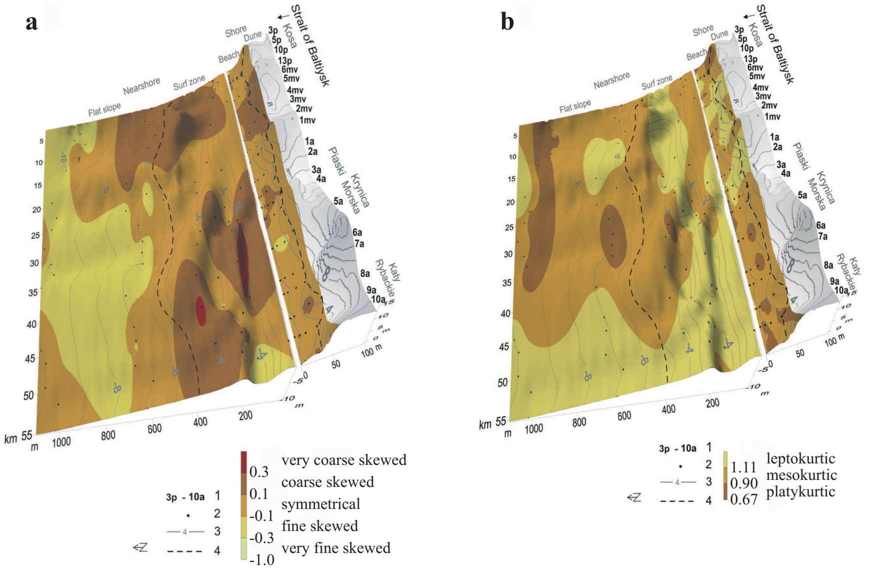

Figure 5. Grain-size indices: a) skewness (Sk_G); b) kurtosis (K_G), of the surficial sediment along the coastal zone of the Vistula Spit, calculated by Folk & Ward's method (1957). 1 – shore and nearshore cross profiles; 2 – sampling location; 3 – isobaths and contour lines; 4 – the border between morphological zones (surf zone and flat nearshore slope; beach and dunes)

Along the Sambian Peninsula coast, from Yantarny in the direction of Baltiysk, the mean grain size (M_G) and sorting (σ_G) decrease from 0.65 to 0.38 mm and from 1.69 to 1.45 respectively (Figure 6). On the stretch

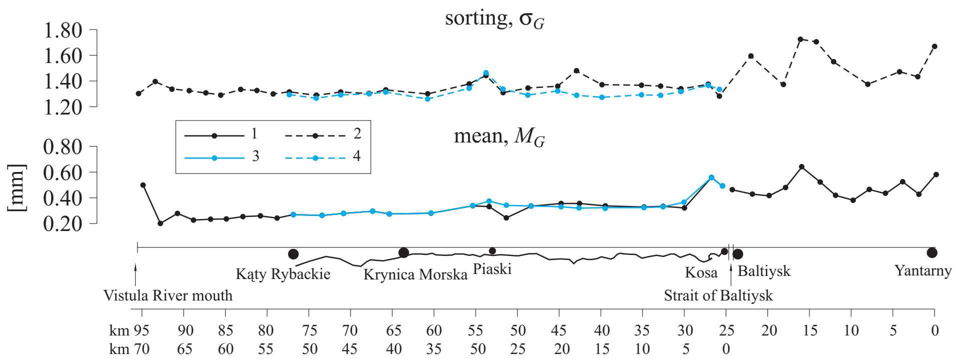

Figure 6. Mean grain size (M_G) and sorting (σ_G) of the shore sediment: 1, 2 – collected from the whole width of the beach (according to the methodology of the P. P. Shirshov Institute of Oceanology, RAS), 3, 4 – collected separately from shore morphological forms (arithmetic average). Calculated by Folk & Ward's method (1957)

located 13–15 km from Yantarny, the mean (M_G) is the highest (0.67 mm) and sorting (σ_G) is the worst (1.7) (Figure 6). The indices are highly changeable on the Sambian Peninsula shore, near the Strait of Baltiysk, at the Vistula River mouth, locally near Piaski and 15–20 km from the strait (Figure 6). With the exception of these anomalies, the mean values (M_G) display a decreasing tendency from the Strait of Baltiysk towards the west (Figure 6).

The mean grain size (M_G) of sediment collected by the two different methods is better comparable than the sorting (σ_G) (Figure 6). The respective correlation coefficients of the mean (M_G) and sorting (σ_G) are 0.92 and 0.74. The maximum difference between the indices is 13%.

4. Discussion

4.1. Lithodynamic interpretation of the results

To determine the lithodynamic conditions of the Vistula Spit coastal zone, a comprehensive analysis of all grain-size indices was performed. The confidence interval for the standard deviation of the mean (M_G), sorting (σ_G), skewness (Sk_G) and kurtosis (K_G) was calculated with a confidence level of 90%. Positive and negative anomalies of these indices can be interpreted as redeposition (erosion) or deposition (accumulation) according to the method of Baraniecki & Racinowski (1996) (Table 3).

Relative decreases in sorting, mean, skewness and kurtosis values (grain diameter in mm) are usually interpreted as deposition, and inverse changes of these data are typical of erosion (Racinowski et al. 2001). Therefore, erosive trends are indicated by positive anomalies (grain size in mm, calculated by Folk & Ward's method (1957)), and deposition by negative anomalies (Table 3, Figure 7). Environments with grain-size indices within the limits of the confidence interval were interpreted as 'stable' (balanced between accumulation and erosion or transitional) (Table 3, Figure 7). Since the confidence interval should be representative, it was calculated separately for the sediment collected from the beach, surf zone (0.9–6 m depth) and the deeper nearshore (7 m and 10 m depths) (Table 3, Figure 7).

Values within the limits of the confidence interval of four, three or two grain-size indices (balanced environment, symbols 01, 02 and 03) were observed in 80% of the samples (Table 3, Figure 7). In the study area, there were no samples indicating deposition in four or three grain-size indices (Table 3). Deposition for two indices was observed in 6.8% of the samples, located in the surf zone (profiles 6mv–1mv, 8a–10a, 4a, Figure 7) and on the coast (profile 5a, Figure 7). Erosion (symbols R1, R2, R3, R4, Table 3, Figure 7) was observed in 13.2% of the samples, located along the lower coast

Table 3. Lithodynamic evaluation of grain-size indices: mean (M_G), sorting (σ_G), skewness (Sk_G) and kurtosis (K_G) (grain diameter in mm) on the basis of the confidence interval, calculated for the standard deviation with a confidence level of 90%

Anomalies of 4 grain-size indices ('0' within the confines of the confidence interval; '–' negative anomaly; '+' positive anomaly)	Lithodynamic interpretation of anomalies		% of samples
	Symbol	Description	
– – – –	D1	deposition (accumulation)	0
– – – and one different	D2		0
– – 0 0	D3		5.1
– – and two different	D4		1.7
0 0 0 0	01	balanced between accumulation and erosion (transit)	12.6
0 0 0 and one different	02		53.7
0 0 and two different	03		13.7
+ + and two different	R4	redeposition (erosion)	4.6
+ + 0 0	R3		4.6
+ + + and one different	R2		3.4
+ + + +	R1		0.6

(profiles 3p–13p, 5mv–3mv and 4a, 6a, Figure 7), in the troughs between longshore bars (profiles 8a–2a, Figure 7), near the Strait of Baltiysk at depths of 0.9–7 m (profiles 3p–5p and 6a, Figure 7) and on the 10 m deep slope (profiles 3p and 3mv, Figure 7).

The dynamics of the sediment, indicated on the basis of the Passega diagram, decrease from the swash and surf zones (depth of 30 cm and troughs), where material is transported by rolling and sliding with high dynamics and local turbulence, towards the deeper flat slope, where fractional transport in the suspended load is dominant (Figure 7). The exception is the area adjacent to the Strait of Baltiysk, which has a dynamic environment and a bed load deficit (Figure 7).

According to the Hjulström diagram, the critical erosive velocities of currents differ significantly along and across the study area. Along the low coast and the surf zone, currents of 18 cm s^{-1} initiate large-scale transport of bed material (Figure 7). However, in the troughs and along the swash zone total redeposition begins at velocities > 20 cm s^{-1} (Figure 7). Along the deeper nearshore, between profiles 4mv and 10a, critical velocities increase from 18 cm s^{-1} to 19–20 cm s^{-1} (Figure 7). To the north-east of profile 4mv, at the depth of 10 m, an inverse, decreasing, trend to 17–18 cm s^{-1} is observed (Figure 7). This phenomenon is due more to the cohesion of the

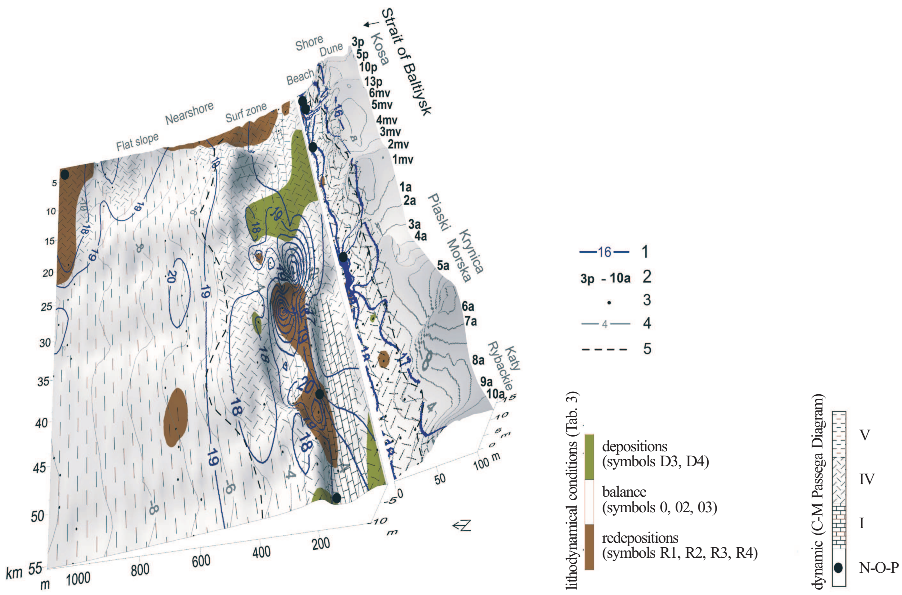

Figure 7. Lithodynamic conditions and sediment dynamics along the Vistula Spit coastal zone, according to the evaluation of 4 grain-size indices, on the basis of the confidence interval (Table 3), Passega diagram (1964) and Hjulström diagram (1935). Fields of the Passega diagram: NOP – high dynamics, local turbulences, I – transport as bed load by rolling and sliding, relatively high dynamics, IV – transport as bed load and graded suspension, mostly by saltation, V – fractional transport in graded suspension, relatively low dynamics. 1 – the critical current velocities [cm s^{-1}] causing redeposition; 2 – shore and nearshore cross profiles; 3 – sampling location; 4 – isobaths and contour lines; 5 – the borders between the surf zone and the flat nearshore slope, and between the beach and dunes

surficial layer of sediment than to the grain size, and indicates lower erosive resistance.

The open-sea coast of the Vistula Spit consists of erosive and accumulative stretches (Zawadzka-Kahlau 1999, Boldyrev & Bobykina 2001, Bobykina & Karmanov 2009). Depending on the shore's exposure to wind-generated waves, some of those stretches are relatively stable while others are changeable. Boldyrev & Bobykina (2001), Chechko et al. (2008) and Bobykina & Karmanov (2009) indicated a stable erosive trend of the coastal zone located near the western pier of the Strait of Baltiysk with a rate of 0.8–4 m $year^{-1}$ (Bobykina & Karmanov 2009). The piers of the Strait of Baltiysk, built at depths of 0–10 m and crossing the surf zone, constitute a local barrier to the bed material, partly deposited near the eastern pier. Moreover, the adjoining area is affected by the flows and sediment transported through the strait from the Vistula Lagoon (Chechko

2007). The decreasing trends of the mean (M_G) and sorting (σ_G) values from Yantarny to the south-west confirms the predominant direction of sediment transport along the Sambian coast (Figure 6). The short transport and quick deposition is registered by rapid changes in the indices (Figure 6). A similar effect is recorded by the significant changeability of the mean (M_G) and sorting (σ_G) on the 5 km long stretch located near the Vistula mouth, with an accumulative rate of about 4–6 m year^{-1} (Zawadzka-Kahlau 1999) (Figure 6).

Owing to the concave deformation of the coastline, longshore sediment transport is directed from the north-east and the south-west, and the convergence zone migrates significant distances under the influence of relatively small changes in the direction of wind-generated waves (Kobelyanskaya & Leont'yev 2011). In accordance with the wind direction during the research in July–September 2008 (SW-WN, 72.9%), the convergence zone was migrating along the central and north-eastern part of the spit.

The character of the 11 km long stretch located on profiles 16p–4mv, and also that of the 4.5 km long stretch located between profiles 9a and 10a, is balanced and accumulative. To the east of profile 9a (profiles 8a–5a) the coastal zone area is balanced and erosive, with a bed load deficit (Figure 7). The predominant north-easterly direction of the local longshore currents is shown mostly by the variability in the sorting (σ_G) (Figure 6). In the central part of the Vistula Spit (profiles 3mv–4a), the sediment dynamics is highly variable, with a high probability of significant influences of the across-shore movement of the bed material.

4.2. Conclusions

1. The coastal zone along the Vistula Spit comprises one or two foredunes 1–14 m high, a beach 10–45 m wide, 0–2 nearshore bars 0.3–1.9 m in height, and a flattish slope, inclined 0.1–0.6°.

2. The nearshore zone with bars (surf zone) is inclined 1.5–2° and delimited by depths of 5.3–6 m.

3. According to the lithodynamic evaluation of four grain-size indices – mean (M_G), sorting (σ_G), skewness (Sk_G) and kurtosis (K_G) – the coastal zone is characterized by balanced conditions (78.6% of the area analysed), with equilibrium between deposition and erosion, and by environments with depositional (8.2% of the surface) and erosive (13.2%) trends.

4. Comparison of the different methods of shore sediment sampling shows the similarity of the results within the limits of the correlation coefficient, amounting to 0.92 (mean (M_G)) and 0.74 (sorting (σ_G)).

5. Along the swash zone, in the troughs between the longshore bars and on the 400 m long segment near the Strait of Baltiysk, bed material is transported by rolling and sliding, with high dynamics and local turbulence. At depths of 7–10 m fractional transport in the suspended load is dominant. There is a bed load deficit on the 3.2 km long stretch adjacent to the Strait of Baltiysk and 48.6–38.1 km from the strait.

6. According to the hydro-meteorological conditions during the research and the variability of the grain-size indices, the resultant longshore sediment transport is directed from the north-east and south-west, and the convergence zone migrates significant distances along the central and north-eastern parts of the Vistula Spit.

7. The critical velocity of currents, causing massive redeposition, varies from 17–18 cm s^{-1} on the low coast, longshore bars and north-eastern part of the deeper slope, to 19–20 cm s^{-1} on the flat nearshore slope, and > 20 cm s^{-1} in the troughs and along the swash zone.

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