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# Wind-Driven Currents and their Impact on the Morpho-Lithology at the Eastern Shore of the Gulf of Gdańsk

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## Abstract

The paper presents results of a study of near-bottom currents, lithology and morphodynamics on the shore-zone of the Vistula Spit in Russia and on the western shore of the Sambian Peninsula. The measurements were conducted in 1991 and during the period of 2005–2009. The study involves the analysis of the synchronous and statistical parameters of the currents together with wind, grain-size and sorting coefficient distributions for the deposits of the beach and underwater slope, and also the analysis of the morphology and morphodynamics along the east coast of the Gulf of Gdańsk. It has been shown that under conditions of an acute angle between the seaward wind vector and the coastline the strongest and the most stable longshore currents are formed. An increase of the angle leads to a decrease of velocity and stability of these currents. Under conditions of the wind normal to the shore (90°) in the sector of the curved coast Yantarny – Baltiysk (west wind), convergence of the currents is observed. The assessments of annual capacities of the longshore sediment transport for the coastal segment at the Sambian Peninsula and the deformation volumes on the underwater slope at Baltiysk are summarized. A hypothesis is proposed that the sector of 5–15 km north of Baltiysk under the existing wind-wave conditions is the zone of convergence and the discharge-resulting sediment transport. The assumption of the prevalence of migratory and whirl circulations along the shore zone of Vistula Spit is put forward. It is noticed that entrance moles of Baltiysk considerably impact on parameters of the currents and flow of deposits along the coastline at the length of 3–4 km.

**Key words:** shore zone, wind, near-bottom currents, lithology, morphodynamics, sediment transport

## 1. Introduction

The east coast of the Gulf of Gdańsk (south-east of the Baltic Sea) comprises west meridionally-oriented coast of the Sambian Peninsula (Cape Taran – Yantarny – Baltiysk, 36 km), Vistula Spit (55 km) and latitudinally-oriented Polish continental coast extended to the Vistula mouth (18 km). The above shore segments form the Sambian-Vistula coastal curve.

The investigations of processes occurring along the coast zone of the Sambian Peninsula have been carried out for more than 100 years. In the pre-war period studies were made by German scientists. In the second part of 20 century – by Russian researchers. In spite of that the knowledge and views on hydro- morpho- lithodynamics at the underwater slope are insufficient, arguable and contradictory. Particulary, the structure and orientation of long-shore currents and sediment transport are not known (Brückmann 1913, Tidemann 1930, Pratje 1932, Zenkovich 1958, Beloshapkov et al 1984, Musielak 1988, Bogdanov et al 1989, Subotowicz 1992, Cieslak 1992, Boldyrev et al 1992, Boldyrev, Rjabkova 2001, Babakov 2003). Accordingly, there is no general view concerning the number of lithodynamics systems and location of their boundaries, the direction of flows of deposits in their limits and the relation between the capacities of long-shore and cross shore. Therefore, it is not possible to estimate the main sources of deposit involvement, transit location and full discharge. By all indications, the lack of knowledge of hydro-, morpho- and lithodynamic processes of coastal zone restrains the elaboration of effective coast-protective methods; their advantages under pressure of growing stormines and the sea level rise, and increasing man-triggered charge in during the development of recreation zones.

The purpose of this study is to complete and summarize the data relating to hydro- litho- morphodynamics processes, and on the basis of collected materials and wind pattern to evaluate the impact of observed currents on the spatial distribution of litho-morphological characteristics and morphodynamics processes at the Vistula and Sambian underwater slope, and then to propose a hypothesis of the most evident area of the flow deposit convergence in the eastern part of the Gulf of Gdańsk.

## 2. Study Area and Materials

The researches of AB IORAS were carried out on the western coast of the Sambian Peninsula and along the Russian territory of the Vistula Spit in 1991 and periodically in 2005–2009 (Fig. 1). Stationary measurements of coastal near-bottom currents in 1991 were made consistently and synchronically at Yantarny (st. 35, 36, 37), and in 3 km northward of Baltiysk piers (st. 38, 39). In 2005 currents were recorded on the basis of measurements consisted of 4 stations (st. 8, 9, 10, 11) south of the Baltiysk entrance piers in September–November, 2005. The prolonged number of measurements north of Baltiysk (st. 6, $H$ = 11 m, between st. 11 and st. 9) were utilized (they were made in April–September, 2004) (Table 1).

The depth measurements of underwater coast slope (UCS) along cross-profiles in the eastern area of the Gulf of Gdańsk were made in 2008 and 2009 by the researches of Laboratory for Coastal System of AB IORAS. Sediment sampling on the beach at the narrow coastal stripe of the UCS ($H$ = 0.3–1.5 m) was conducted along 11 profiles in summer 2009 and carried out with the participation of Polish colleagues from the Institute of Hydro-Engineering of the Polish Academy of Sciences (IBW PAN, Gdańsk), see Fig. 1.

**Table 1.** Geographical coordinates of the pyramids, depths and measurement periods at the Yantarny, Baltiysk cross-profiles, and at the southern range (5 stations south of the Baltiysk Strait)

| Location | Station No. | G. coordinates | | Depth [m] | Periodicity of measurements [hours] | Duration of measurements | Quantity of measu-rements |
|---|---|---|---|---|---|---|---|
| | | Latitude (north) | Longitude (east) | | | | |
| 1991 | | | | | | | |
| Yantarny 26 km north of the strait | 35 | 54°52.0′ | 19°55.7′ | 5 | 1 | 03.08–03.09<br>03.09–16.10 | 1777 |
| | 36 | 54°51.7′ | 19°55.4′ | 10 | 1 | 03.08–28.08<br>03.09–10.09 | 752 |
| | 37 | 54°51.6′ | 19°55.0′ | 15 | 1 | 03.08–03.09<br>03.09–14.10 | 1724 |
| Baltiysk 2.5 km north of the strait | 38 | 54°40.5′ | 19°53.7′ | 8 | 1 | 03.08–16.09<br>16.09–15.10 | 1674 |
| | 39 | 54°40.9′ | 19°52.5′ | 14 | 1 | 03.08–17.09 | 1070 |
| 2004 | | | | | | | |
| 2.5 km south of the strait | 6 | 54°37.987′ | 19°50.884′ | 11<br>11<br>11 | 0.5<br>1<br>1 | 2.04–28.04<br>28.04–18.06<br>18.07–13.09 | 1225<br>1213<br>1354 |
| 2005 | | | | | | | |
| Northern cross-profile (8–9) 0.75 km south of the strait | 8 | 54°38.145′ | 19°52.260′ | 6 | 1 | 12.09–26.09<br>26.09–9.10<br>9.10 – 20.11 | 139<br>0<br>1013 |
| | 9 | 54°38.635′ | 19°51.166′ | 12 | 1 | 12.09 –26.09<br>26.09–8.10<br>8.10–12.11 | 336<br>285<br>848 |
| Southern cross-profile (10–11) 3.5 km south of the strait | 10 | 54°37.197′ | 19°51.090′ | 6 | 1 | 12.09–26.09<br>26.09–9.10<br>9.10–9.10 | 84<br>15<br>0 |
| | 11 | 54°37.563′ | 19°50.333′ | 12 | 1 | 12.09–25.09<br>25.09–8.10<br>8.10–18.11 | 316<br>306<br>970 |

The material from the field research on the west part of Sambian Peninsula was collected by the Kaliningrad State University (KSU) (1971–1975) (Research 1975) and in 1977–1978 (Balajan 1981), Atlantic Branch of the Institute of Oceanology of the Russian Academy of Sciences (2005–2006) (Chechko 2008), and in joint work of Polish and Russian colleagues on the Vistula Spit (2006–2007) (Kobelyanskaya et al 2009). All these investigations were included in this article.

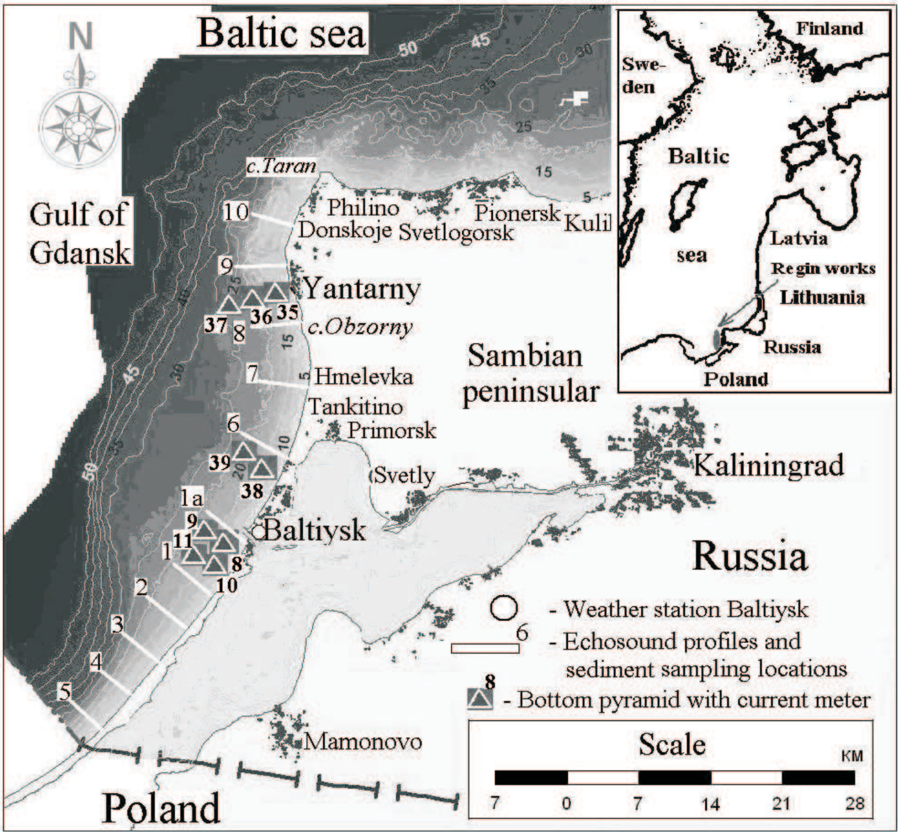


**Fig. 1.** The study area of AB IORAS (1991–2009). Locations of the bottom pyramids and morpho-lithology cross-profiles in the eastern part of the Gulf of Gdańsk

## 3. Work Methods

### 3.1. Wind Measurements

The observations of wind parameters are continuously recorded at the weather station in Baltiysk. At the beginning of each hour the wind parameters are measured for 10 minutes and averaged.

### 3.2. Current Measurements

Current recorders (BPV-2) are based to measure near-bottom currents. These recorders are fixed inside near-bottom pyramid. To avoid distorting wave influence, the bottom recorders (BPV-2) were connected with the base of pyramid, and the rope tied down to a rotated cylinder. The propeller was fixed 1 m above the bottom. The measurements were registered each hour (Fig. 2). The placement of the pyramids was carried out by power boats (Fig. 3).

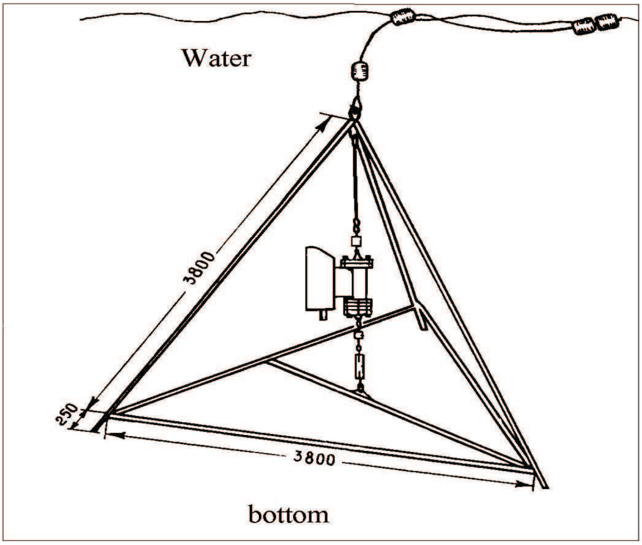


**Fig. 2.** Bottom pyramid with self-recording current meter BPV-2

**Fig. 3.** The moment of arrival at the station to mount a pyramid with self-recording current meter BPV-2

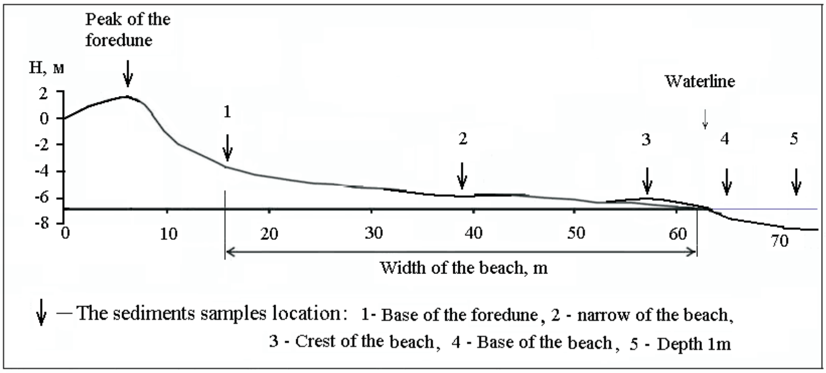


**Fig. 4.** Location of the sediment samples along the cross-profile of beach and underwater slope

### 3.3. Lithology Measurements

Sand sampling along the cross-profiles 1a, 1, 4, 6, and 9 was carried on a beach at 3 points: at the base of a dune (1), at trough of beach (2), on the crest of beach (3), and on an underwater coastal slope (UCS) at 2 points: at the beach basis (4) and at the depths of 1.2–1.5 m (5) (Fig. 4).

Samples, referred to as "mean beach samples", were collected along cross-profiles 2, 3, 5, 7, 8, 10 (Fig. 1). This method involved collecting a single surface sample from the entire width of the beach from the waterline to the base of the fore dune. Sieves with the mesh of decimal scale: 10; 7; 5; 3; 2; 1; 0.5; 0.25; 0.15; 0.05 mm were used to analyze grain-size distribution (Petelin 1967). Results of the analysis were used to plot bar graph curves and calculate the mean grain size $D_{50}$ and the sorting coefficient $So$ (Trask 1930).

### 3.4. Morphology Measurements

The measurement of depths was carried out by echo sounder combined with GPS in a range of depths from 2 to 13–15 m, with a frequency of 6 seconds (Fig. 1).

## 4. Results and Discussion

### 4.1. Wind

Wind pattern in the Gulf of Gdańsk is characterized by the dominance of winds from the western rhumbs, especially, at speeds $W > 5$ m/s (Fig. 5).

The wind ($V > 10$ m/s) is frequently directed from "SW" – "W" – "NW" rhumbs. As a result, westerly winds influence the Vistula Spit coast at acute angle and close to normal direction (90°) toward the western coast of the Sambian Peninsula. Waves reaching the coast refract, but long-shore component (from the west to the east) are preserved.

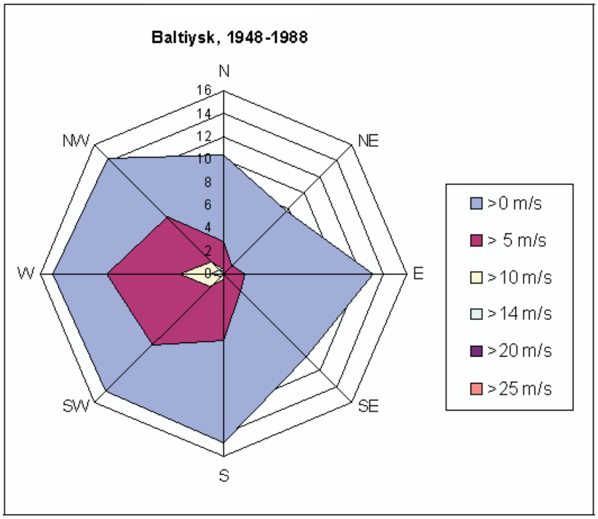


**Fig. 5.** Wind rose according to long-term measurements at the weather station in Baltiysk (1948–1988) (Courtesy of Chubarenko B. and Stont Zh.)

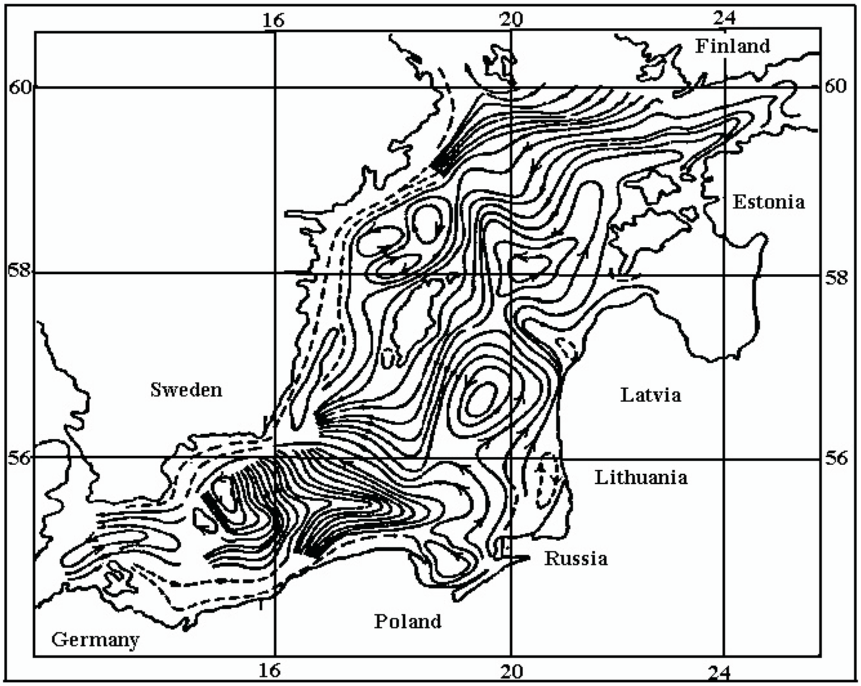


**Fig. 6.** The geostrofic currents according to natural hydrological observations (Soskin et al 1963)

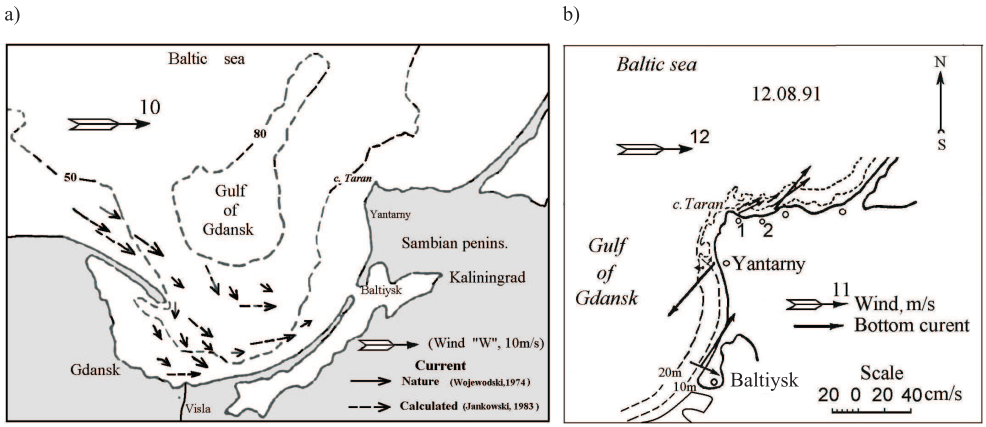


**Fig. 7.** The near-shore current vectors under the western wind in the western and southern parts (a) (Processes 1987 ) and in the eastern part (b) (Babakov 2003) of the Gulf of Gdańsk

## 4.2. Currents

The dominance of western winds and waves lead to the formation of a large-scale cyclone circulation in the area of the Gulf of Gdańsk. The circulation occurs counterclockwise and is observed as a field of quasi-permanent and geostrofic currents, constructed on the basis of natural hydrological observations and current schemes.

The meanders of circulation currents enter the coastal zone of the Gulf of Gdańsk. Their activity is particularly evident in the area of Yantarny – cape Taran. At Yantarny at a depth of 15 m (station no. 37) an intensification of northern shore current is registered (azimuth 340°) to 106 cm/s in the periods of strong “S” wind ($V$ = 15 m/s) and with “SW” wind ($V$ = 11 m/s) to 60 cm/s. At the same time, at the shallow stations, the speed was less. 12 km northward of cape Taran, in the zone an isobath of 56 m on the horizon 25 m, a stable flow of northward current at 40–60 cm/s is registered throughout 24 hours (Babakov 2003).

In the coastal zone of the western and southern part of the Gulf of Gdańsk, the currents at “W” wind hold the same eastward direction along the coasts of Hel Penisula and the Vistula Spit (Fig. 7a). However, at the Sambian Peninsula coast, the angle of the wind-wave approach became normal. At a depth 12–15 m, near-bottom currents preserve their cross direction with maximum recurrence to the shore. At 1 m off the bottom the flow towards the shore dominates over the compensation outflow, that jet running farther off the shore rises in the middle of the horizon (Speransky 1973). The turn of currents along the long-coast wind component starts in the zone of isobathic 10 m. Consequently, at “W” wind in the centre of Yantarny – Baltiysk concave, the system of countercurrents is observed: from Baltiysk to the north, and from Yantarny to the south (Fig. 7b).

a) b)

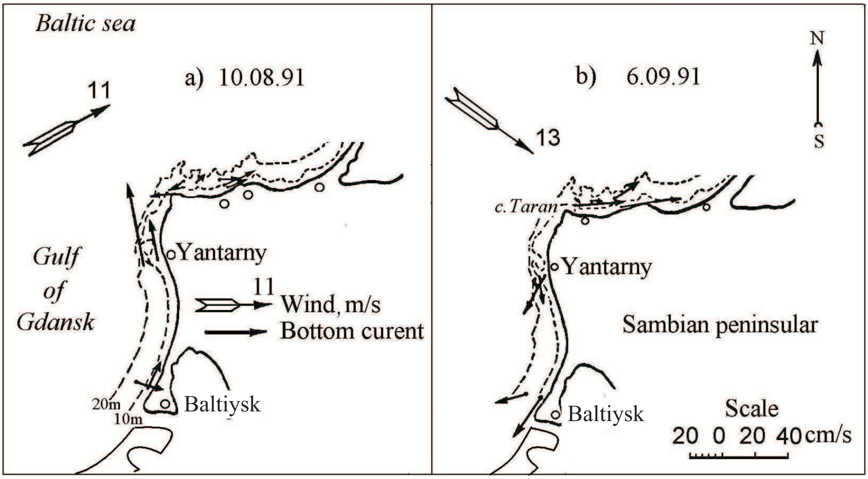


**Fig. 8.** Synchronous distribution of the near-bed currents during the acute-angle directional wind to the Sambian shore (Babakov 2003)

a) Wind b) Current

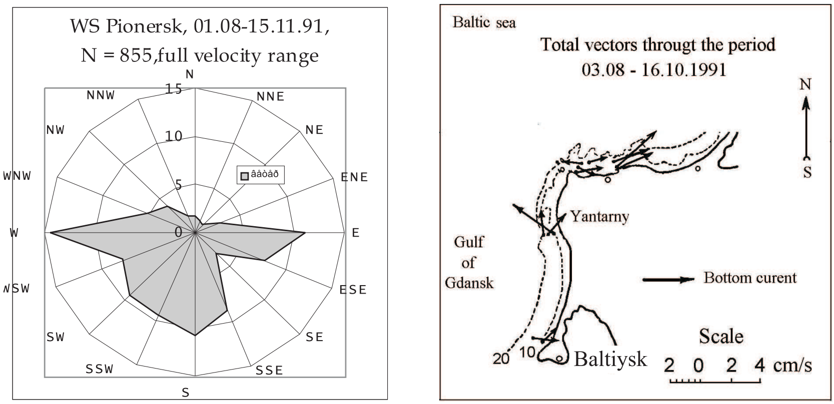


**Fig. 9.** Wind rose (a) and resulting vectors of the near-bed currents on the Sambian shore for the period 03.08–16.10.91

The change of seaward wind direction causes an appropriate shift of the convergence zone of currents to the area of normal wind approach toward the shore. The change of currents parameters corresponds to the change of wind parameters within 3 hours. In the case of a wind approaching the shore at acute angles, the spatial structure of coastal currents becomes unidirectional, with the long-shore wind component (Fig. 8).

According to the statistics, the average high correlation between the direction of the prevailing wind and resulting water flow along the whole western coast of the Sambian Peninsula remains the same (Fig. 9).

The orientation of near-bottom currents along the coastal component of the wind, measured at the Vistula Spit, are distinctly observed. At an increasing speed of wind, the close connection is growing (Fig. 10).

The velocities of near-bottom currents in the zone of measurements are mostly not more than $V = 10$ cm/s. The recurrence at the shallow station (depth 5–8 m) (stations 10–8–38–35 from the south to the north) is 67.8% – 84.0% – 90.8% – 85%, while at the deep station (depth = 11–15 m) (stations 11–9–39–37) relatively – 90.9% – 92% – 92.7% – 96.0% (see Fig. 1 for the locations of the stations). The recurrence of the velocity ($V > 10$ cm/s) for the shallow stations is relatively 29.0% – 15.5% – 9.1% – 14.2%, while for the deep stations is 9.6% – 8.0% – 7.3% – 2.2%. It is necessary to notice that at depths 5–8 m the recurrence of intensive currents ($V > 10$ cm/s) is maximum (29.0%, station 10) at the Vistula ground measurements and at Yantarny (14.2%, station 35). The recurrence of slow currents ($V = 10$ cm/s), in contrast, is maximum (90.8%) 3 km north of the Baltiysk Strait. The observed maximum velocities of near-bottom currents at the shallow station (st. 10–8–38–35) are – 54 cm/s – 45 cm/s – 29 cm/s – 61 cm/s, along the deep stations (st. 11–9–39–36) – 34 cm/s – 44 cm/s – 34 cm/s – 49 cm/s. The observed velocity increases south of the piers (Vistula Spit) and is explained by the acute angle of the western storms segment toward the coastal line, and in Yantarny sector by the increase of "S" and "SW" wind.

## 4.3. Lithology

On the whole, one observes the tendency towards sediments' reduction in sizes from the north to the south in the coastal zone of the eastern part of the Gulf of Gdańsk.

### *4.3.1. Sambian Peninsula*

The beach is well sorted ($S_0 = 1.25$–$1.5$) by medium sand ($D = 0.25$–$0.50$ mm), with a median diameter $D_{50} = 0.24$–$0.31$ mm on the coast of the Sambian Peninsula (Donskaya Bay – Baltiysk). Its content in sediments reaches 75–90% (Table 2, point 1–3, Fig. 11a–c).

Deposits' coarseness considerably varies from the north to the south on the underwater coastal slope. The median diameter decreases from 1.12 mm in the Donskaya Bay (profile 10) to 0.28 mm near to Baltiysk (profile 6) and to 0.31 mm in the narrow coastal strip (depth = 2–5 m) (Chechko et al 2008).

The local minimum of grain-size ($D_{50} = 0.17$ mm) and maximum level of sorting ($S_0 = 1.5$) (Table 2, points 4–5, Fig. 11d, e) are observed in the centre of the Yantarny-Baltiysk concavity of the coast (profile 7).

Medium sands with impurities of large and small fractions prevail at depths up to 10–12 m in the Donskaya Bay. Stony and block shoals as well as gravel and pebbled

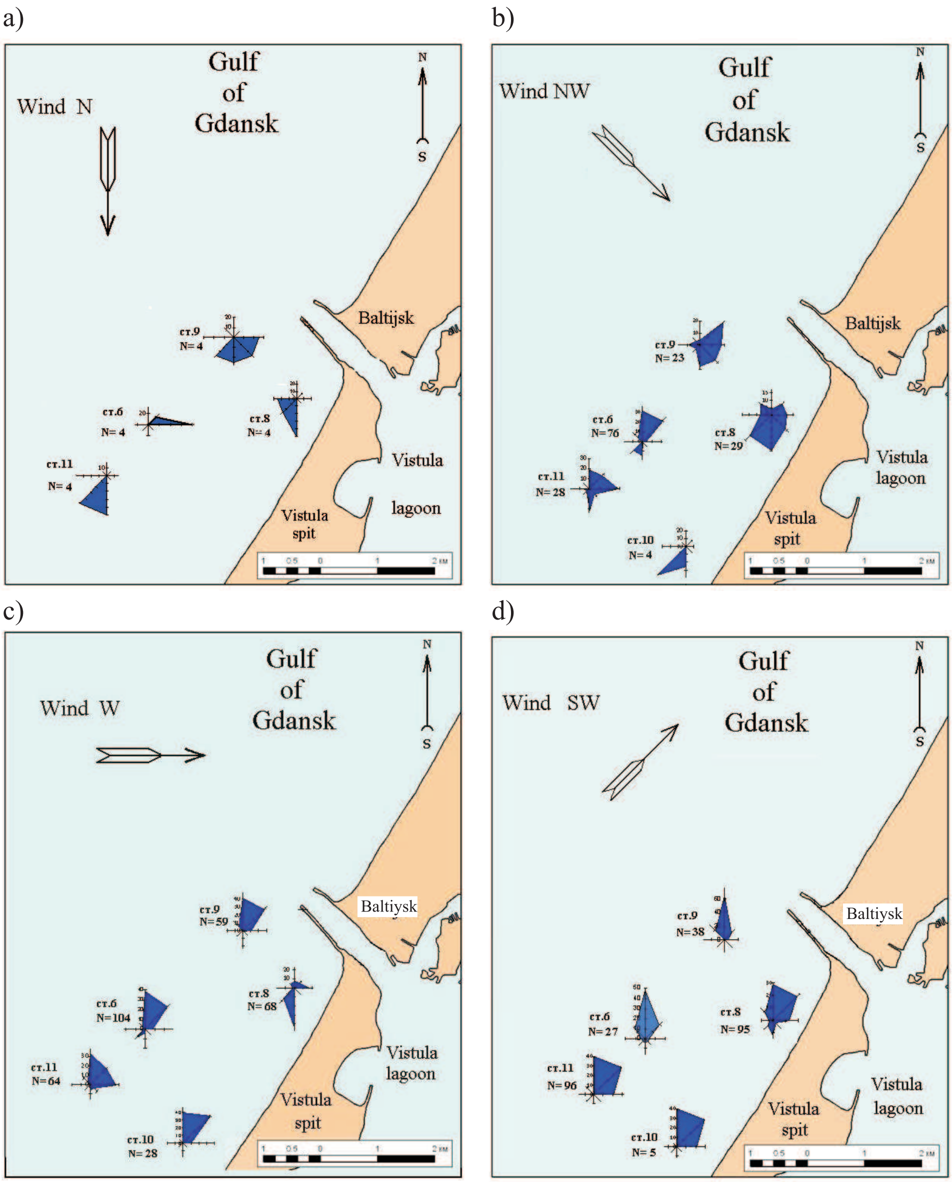


**Fig. 10.** The roses of the near-bottom currents at the concrete compass points of a moderate and strong wind ($W > 8$ m/c, 12.09–20.11.2005) (Babakov 2008)

**Table 2.** Mean grain size ($D_{50}$, mm) and sorting coefficient ($S_0$) for beach (points 1–3) and for seabed deposits in shallow near-shore (point 4–5, $H = -0.3$ m and $-1.5$ m) along the eastern part of the Gulf of Gdańsk (4–5.08.2009), see Fig. 1 for locations of the measuring profiles

| Location | Latitude / Longitude | Distance from the Baltiysk | $D_{50}/S_0$ Point 1 | Point 2 | Point 3 | Point 4 | Point 5 |
|---|---|---|---|---|---|---|---|
| West coast of the Sambian Peninsula (Donskaya Bay – Baltiysk) 05.08.09 | | | | | | | |
| Profile 10 Average | 54°56.371′ 19°57.70′ | 33.8 km | 0.31/1.31 | | | 1.12/1.19 | 0.63/1.42 |
| Profile 9 | 54°51.473′ 19°56.045′ | 24.6 km | 0.24/1.34 | 0.29/1.24 | 0.26/1.26 | 1.02/1.28 | 0.26/1.26 |
| Profile 8 (Average) | 54°49.014′ 19°57.328′ | 20.2 km | 0.27/1.28 | | | – | 0.26/1.30 |
| Profile 7 (Average) | 54°43.663′ 19°56.668′ | 10.7 km | 0.31/1.52 | | | – | 0.17/1.50 |
| Profile 6 | 54°40.906′ 19°54.745′ | 4.9 km | 0.27/1.22 | 0.29/1.25 | 0.28/1.24 | 0.98/1.33 | 0.28/1.25 |
| Vistula Spit (Baltiysk – Russian-Polish border) 4.08.09 | | | | | | | |
| Profile 1a | 54° 37.564′ 19° 52.134′ | 1.6 km | 0.29/1.24 | 0.29/1.24 | 0.29/1.23 | 0.64/1.55 | 0.31/1.35 |
| Profile 1 | 54°35.293′ 19°49.587′ | 6.7 km | 0.27/1.26 | 0.30/1.26 | 0.26/1.29 | 0.28/1.26 | 0.23/1.43 |
| Profile 2 (Average) | 54°34.093′ 19°48.034′ | 9.3 km | 0.28/1.27 | | | – | 0.18/1.49 |
| Profile 3 (Average) | 54°32.378′ 19°45.665′ | 13.4 km | 0.24/1.40 | | | – | 0.20/1.49 |
| Profile 4 | 54°30.235′ 19°42.523′ | 18.4 km | 0.24/1.35 | 0.25/1.39 | 0.24/1.35 | 0.26/1.29 | 0.23/1.42 |
| Profile 5 (Average) | 54°28.875′ 19°40.598′ | 21.9 km | 0.22/1.45 | | | – | 0.16/1.48 |

deposits are observed more deeply (Depth > 10–12 m). The zone of sand deposits extends to the southern accumulative area, from Cape Peschanij to Baltiysk (profile 8–6) (Research 1975). Well sorted fine sands ($D = 0.1$–$0.25$ mm), with median diameter $D_{50} = 0.14$–$0.18$ mm, prevail in the centre of the Yantarny – Baltiysk concavity (profile 7) (Table 2). Medium sands ($D_{50} = 0.36$–$0.42$ mm) are located only near the northern pier of Baltiysk in the narrow coastal strip. The strip extends toward the north 2–3 km from Baltiysk and toward depths of 5 m (Chechko et al 2008).

### 4.3.2. *Vistula Spit*

The largest deposits are located near the southern Baltiysk pier (on a beach and at the bottom) at the Vistula Coast. Their coarseness decreases from Baltiysk to the south, to the Russian-Polish border, but the character of change on the beach and at the Vistula Spit are various.

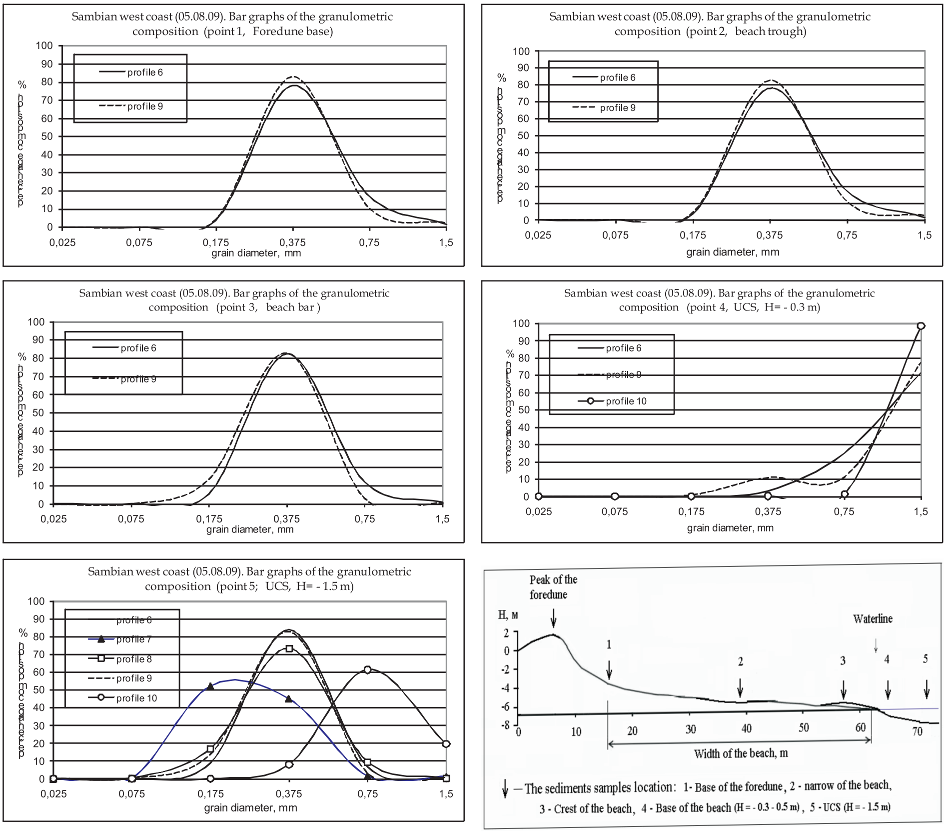


**Fig. 11.** Grain-size distributions for the deposits, detected along the Sambian coast (Yantarny – Baltiysk, profiles 6–10) for each point (1–5) of the profile

The beach (Table 2, points 1–3) near the pier is formed by medium sand (84%, $D_{50}$ = 0.29 mm), with well sorting coefficient ($S_0$ = 1.23–1.24). Deposits' coarseness and share of medium sand decrease in a direction of the south. Medium sand ($D_{50}$ = 0.26–0.30 mm, profiles 1a–2) still prevails within the distance of 10 km from the south pier, content of fine and medium fractions is identical within 10–20 km from the pier ($D_{50}$ = 0.24 mm, profiles 3–4), and fine sand slightly prevails already near border ($D_{50}$ = 0.22 mm, profile 5). Sand sorting has the reversed tendency (Table 2, Fig. 12, diagram 12a–d).

A share of medium sand in the narrow coastal strip (depth = 0.3–1.5 m, points 4–5) in the Russian part of the Vistula Spit reduces from 68% to 38%, from the north to the south; a share of fine sand increases accordingly from 33% to 59%. However, the average size of sediments varies unstably: it decreases ($D_{50}$ = 0.31–0.18 mm) at the segment 0–10 km of the northern part (profile 1a–2), and it increases at the following segment with a length 9 km (profiles 3–4) ($D_{50}$ = 0.18–0.23 mm), and again it

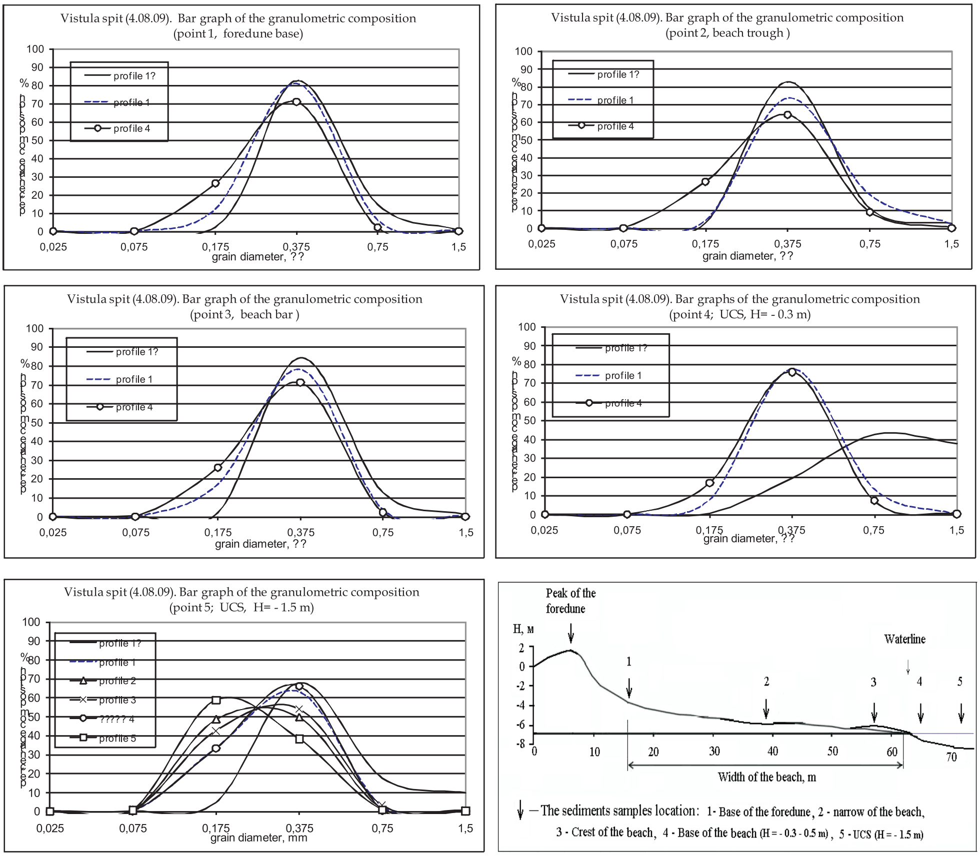


**Fig. 12.** Grain-size distributions for the deposits, detected along the coast of the Vistula Spit (2009) for each point (1–5) of the profile. Locations of the points see Fig. 4

decreases at the border ($D_{50}$ = 0.23–0.16 mm). Sorting at all the sectors (1.35–1.49) is good organized and it changes in phase opposition with deposits' coarseness (Table 2).

Alternation of sediments'coarseness was also observed in the underwater part of the beach (at the lower beach) in the western section of the Vistula Spit (Kobelyanskaya et al 2009). One can see the following varying and dynamic picture at the bottom near the southern pier: fields of fine sand alternate with the centres of coarse-grained sand, gravel and a pebble; they are observed constantly at the depth of 12–18 m, and they are periodically covered by fine sand (depth = 1–6 m). However, fine sand prevails on the submarine coast slope at a distance of 3 km from the south pier, and further to the south its content in bottom sediments reaches 85% with $S_0$ = 1.32–1.97 (Chechko et al 2008).

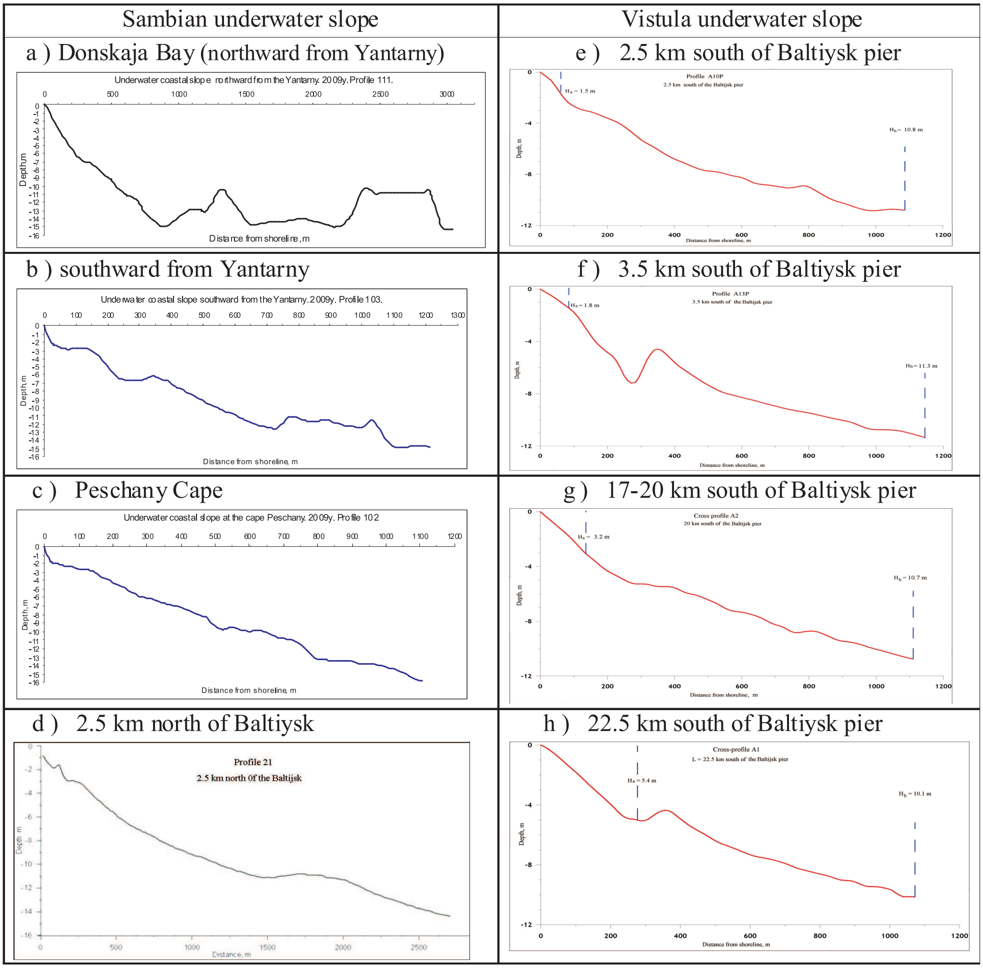


**Fig. 13.** Underwater coastal slopes on the western coast of the Sambian Peninsula (a) and on the Vistula Spit (b) (echo-sounding, 2008)

## 4.4. Morphology and Morphodynamics

There is the tendency of a decreasing decline of underwater coast slopes (UCS) from Cape Taran to the south on the western coast of the Sambian Peninsula. The most abrupt slopes are observed on the zone Cape Taran – Donskaya Bay and on the opposite side of the capes (to 0.025–0.035) (Fig. 13a, c). The slopes are minimum (0.008) in the centre of the Yantarny-Baltiysk concavity at a distance of 100–1.000 m from the coastline; in Baltiysk – 0.009–0.012.

Underwater bars in the coastal zone of the Sambian Peninsula start to be formed in a place of pulp discharge of the Yantarny amber plant, and a saturation along the coastal flow of the deposits. Bars elevation here is less than 1 m, remoteness of bars from the coast is mainly 120–350 m, and depths over crests are 2.5–5.5 m (Fig. 13b). Bars degrade and disappear (Fig. 13d) opposite to the capes and at the top of Yantarny-Baltiysk concavity (Hmelevka-Tankitino). They are observed to the south again, but they are less developed (Fig. 13d).

A maximum decline of UCS (0.020–0.025) is observed near the southern Baltiysk pier at the Vistula coast (Fig. 13e). Then the decline of the slope diminish to 0.015–0.012 southwards. The formation of the submarine bar begins at a distance of 1–1.5 km southwards from the pier; it has already a well-shaped configuration at a distance of 3–3.5 km (Fig. 13f). The second submarine bar is formed within the length of 3.5–10 km. Both bars are well shaped, continuous and stretch along the coast shore at a distance of 130–150 m and 300–400 m. However, they are degrading at a distance of 17–20 km from the piers (Fig. 13g), and again they are observed at a distance of 22 km, near the border (Fig. 13h). On the average, the crests of the underwater bar of the Vistula Spit settle down in 130–200 m and 300–450 m from the coastline, within isobaths of 1–2 m and 3–5.5 m.

On the whole, the tops of the bars are located at a distance of 150–220 m and 300–450 m from the water line, within isobaths 1–2 m and 3–5.5 m on the Russian territory of the Vistula Spit. According to a satellite photo dated May 2010 (by Google), seaward bar is washed away and closed with coastal bar in the distance of 3.5 km to the south off the Polish border. The seaward bar is not observed on the $9^{th}$ km (Piaski-Krynica Morska), and there are two bars – in 70 and 80 m and in 200–230 m from the edge of the $12^{th}$ km.

It was revealed during the measurement of the deformations of a submarine slope in the sector 2 km adjoined to the northern pier of Baltiysk (6.08.71–5.02.75) that there had been accumulated 3.46 million $m^3$ or 988 thousands $m^3$/year. 80% of all deposits were accumulated at depths of 4–12 m, near to the tip of the northern pier (Research 1975). Similar calculations of deformations during 17 years (1988–2005 years) showed an accumulation of this area of the volume of 8.3 million $m^3$ (490 thousands $m^3$/year). The powerful accumulative corpus was located at a distance of 3–5 km to the north off the Baltiysk Strait, within the depths of 8–15 m. A less active accumulation was observed at a depth of 3–5 m, in the form of a strip extending along the coast. Thereby there is not revealed any stable tendency to submarine slope's deformation in the south off the piers (Chechko et al 2008). Apparently, a decrease in annual volumes of accumulation is connected with a sharp decrease in sand dumping by Yantarny amber factory into the sea; it had been decreased to 24 thousands $m^3$/year by 1999 (Fig. 14).

It is worth mentioning that volumes of short-term deformations of the submarine slope can exceed annual average sizes. According to the echo sound observations (1978 year), there was accumulated 1.3 million $m^3$ on the second km of the area to the north off Baltiysk for 2 months (Balajan 1981). For comparison, there was an indicated accumulation of up to 710 thousands $m^3$ on the northern abrasive coast of

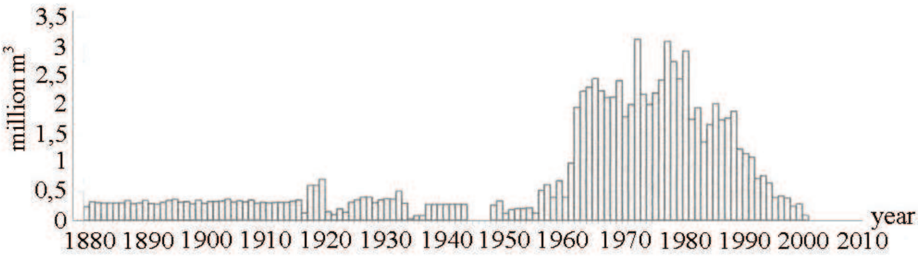


**Fig. 14.** Long-term dynamics of sand dumping by Yantarny amber plant into the sea (Bass, Zhindarev 2007)

the Sambian Peninsula, in the Svetlogorsk Bay (*L* = 4.8 km), for 2 months, whereas for the next year there was 50 thousands m$^3$ (Babakov 2003).

Thus, the capacity estimations of the alongshore flow of deposits near the Baltiysk vary within 90–200 thousands m$^3$/year (Boldyrev, Zenkovich 1982, 1990, Beloshapkov et al 1984). The correlation between the capacity of the flow deposits and volumes of deformations of the underwater coastal slope testifies that the migration, especially the cross one, exceeds the resultant sediment transport during the storm periods.

## 5. Conclusions

The combined analysis of near-shore currents and wind shows that the currents start orienting along the coastal component of the wind at a speed of more than 6–7 m/s. The curved coast of the Gulf of Gdańsk causes an essential change of the current structure along the coastline. In the period of dominant wind activity from western directions, the stable northward currents are observed in the area of the Vistula Spit adjoining the Baltiysk south pier. When an acute angle between the seaward wind vector and the coastline is observed, the strongest, and the most stable currents are formed. In the case when the angle between the wind vector and the coastline increases, the alongshore wind component decreases and the longshore current velocity is smaller. Under conditions of the normal wind to the shore (90°), which are more frequent on the western coast of the Sambian Peninsula, near-bottom currents (1 m from the bottom) at the depth of 12–15 m are most often oriented towards the coast. In the zone of isobaths of 10 m, the currents begin to alter their direction along the coast. In a sector of the Sambian Peninsula (Cape Peschanij – Parashutnoe) the current component along the shore caused by western wind change its direction, which leads to an appearance of southward directed currents. Thus, in the area of the curved coast Yantarny – Baltiysk, a convergence of the currents is observed under the western wind. The change of the wind direction effects an adequate shift of the location of the convergence zone.

Direct observations (at wind speed of $W$ = 12–15 m/s) show that the maximum breadth of the currents along the shore can expand to the depth of 14–15 m. Under conditions of storm setup of water level, the compensation currents have the capacity to reach the depth of 15–20 m. The velocity of near-bottom currents at strong winds reach 40–60 cm/s at a depth of 5–7 m and 30–50 cm/s – at a depth of 10–15 m.

On the eastern coast of the Gulf of Gdańsk there is mainly the tendency of downsizing the grain size sediment from the north towards the south. Beach sediments for the coast sector from Donskaya Bay on the Sambian Peninsula up to 10 km on the Vistula Spit (SW of Baltiysk) are formed of medium-grained sand. Farther to the south, towards the Russian-Polish border, fine-grained sand slightly prevails on the beach.

On the north part of the western coast of the Sambian Peninsula, at the underwater slope (depth of 1.5–10 m), fields of the medium grain-size sand prevail, on the deeper site slope (12–18 m) – boulder-bank and the fields of rough and medium grained sand mixed with gravel and pebble are observed. From the centre of Yantarny-Baltiysk curve to the Russian-Polish border, the seabed is composed of fine-grained sand. The sediments along the Vistula Spit are usually finer than in the Sambian coastal zone. Their grain-size minimum is observed near the border. The places where the coarse-grained sands and fine-grained sands alternate each other are observed only on the shore segment 3 km southwards from the Baltiysk piers.

In the centre of the coastal curve Yantarny – Baltiysk, a disappearance (degradation) of the underwater bar, as well as an evident decrease of grain-size of deposits (to $D_{50}$ = 0.17), and a decline of the submarine slope (to 0.08) are observed. Besides, the convergence of coastal currents at western winds is noticed. These facts indicate the change of the hydro-lithodynamics pattern in comparison to adjacent shore zones. It can be supposed that this is caused by the turn of the coastline (40° in the sector Yantarny – Baltiysk) which changes the reach angle of the seaward winds towards the coastline. The normal to the coastline in centre of the above concavity has the azimuth of 290°.

A sudden stoppage of sand dumping by Yantarny amber plant resulted in a double decrease of the volume of accumulation at the underwater slope north of Baltiysk, from 990 to 490 thousand $m^3$ per year. Nevertheless, the process of sediment accumulation continues. The accumulation volume remains more excessive than the assessments of southward sediment transport rate from Yantarny to Baltiysk (90–200 thousand/$m^3$ per year).

The hypothesis is proposed that the long-shore sector of the underwater slope located 5–15 km north of Baltiysk under the existing wind pattern is the zone of convergence of the long-shore sediment fluxes. However, the wind pattern is under temporary changes. Accordingly, the structure of coastal currents alters along the shore so that the convergence zone of the sediment transport migrates and the transport rates are subject to changes too. Consequently, the following hypothesis can be formulated: the entire Vistula Spit coast is the zone of accumulation in the long-term scale of its forming and developing for 9–9.5 thousand years. The indirect argument for the migration of the zones of accumulation and abrasion along the Vistula Spit is the various breadth and height of the Spit, as well as the location of straits, marked in archival documents.

The observed grain-sizes and calculated sorting coefficients indicate that the seabed deposits interchange. Further, the shape of underwater bars also changes along the shore. These features suggest that the local migration of sediments and vortex circulations are the sediment transport patterns which predominate in the Russian part of the Vistula Spit. According to the analysis of the spatial distribution of the parameters of the near-bottom currents, as well as to the morphology of the underwater slope and the grain-size features of the seabed deposits, the distance of disturbing influence of the Baltiysk harbour entrance piers on the dynamics of coastal processes along the shore stretches 3–4 km south-westwards, which is 3–4 times more that the length of the piers.

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## References

Babakov A. (2003) Space-temporal structure of the currents and sediment migrations in coastal zone of south-east Baltic sea (Sambian P. and Curonian spit), Ph.D. dissertation, Kaliningrad, Geographic faculty, KGU, 273 p.

Babakov A. (2008) Near-bed currents south of entrance moles, [in:] Baltiysk according to nature measuring, Dynamics coastal zone of the Sea un flooded, Baltiysk, Proceedings of School-seminar, 30.06–05.07.08, Kaliningrad, Terra Baltica, 31–35.

Balajan B. M. (1981) Deformation of a bottom of a coastal zone of one of sites of southeast Baltic in the conditions of the broken regimen of alongshore sediment transport, UGS, V. 113, Issue 3, 260–264.

Bass O. V., Zhindarev L. A. (2007) Technogenesis in coastal zone of an sand shores for closed sea (Impact of hydraulic engineering activity on morphodynamics of a coastal zone of the south-east Baltic), *Geomorphology*, (4), 17–24.

Beloshapkov A. V., Beloshapkova S. G., Brasavgs G. H. (1984) Features of sediment lithodynamics at the western coast of Sambian Peninsula, Structure of a shelf of the seas USSR as a basis of an estimation of engineering-geological conditions, *Proceedings USRIsea-geo*, Riga, 42–46.

Boldyrev V. L., Lazshenkov V. M. Rjabkova O. I. (1992) Evolution of western coast Kaliningrad region, Evolution of coast in the conditions of a raising of ocean level, Moscow, 212–225.

Boldyrev V. L., Rjabkova O. I. (2001) Dynamics of coastal processes at the Kaliningrad coast of Baltic Sea, *Proceedings RGS*, **133** (5), 41–49.

Bogdanov N. A., Sovershaev V. A., Zhindarev L. A., Agapov A. P. (1989) Evolution of representations about dynamics of southeast coast of Baltic Sea, *Geomorphology*, (2). 62–69.

Boldyrev V. L., Zenkovich V. P. (1982) *Baltic Sea, The Far East and coast of the seas surrounding territory of the USSR*, Moscow, Nauka, 214–218.

Brückmann R. (1913) Beobachtungen über Strandverschiebunden an der Küste des Samlands, Schr. d. phys.-ok. ges., H. III, Leipzig – Berlin.

Chechko V. A., Chubarenko B. V., Boldyrev V. L, Bobykina V. P., Kurchenko V. Yu., Domnin D. A. (2008) Dynamics of the Marine Coastal Zone of the Sea Near the Entrance Moles of the Kaliningrad Seaway Channel, *Water Resources*, **35** (6), 652–661.

Cieslak A. (1992) Sediment transport along coast of Poland, [in:] Studying of the basic patterns and tendencies of coastal line moving of Baltic sea for last 100 years, Editied by Orviky K. Tallinn, 47–54.

Hydrometeorology and hydrochemistry of the seas USSR, V. III, Baltic Sea, Issue 1, Hydro-meteorologycal conditions. Leningrad, Hydrometeoissue, 1992, 449 p.

Kobelyanskaya J., Piekarek-Jankowska H., Boldyrev V., Bobykina V., Stępniewski P. (2009) The morphodynamics of the Vistula Spit seaward coast (Southern Baltic, Poland, Russia), *International Journal of Oceanography and Hydrobiology*, **XXXVIII**, Supplement 1, 1–16.

Musielak S. (1988) Morphodynamics of the coastal zone of the sea without flooded (by the example of the Polish coasts), Abstract Ph. D Habil. (D.Sc.). Moscow: Geographic faculty, MGU, 38 p.

Petelin V. N. (1967) *Granulometric Analysis of Marine Bottom Sediments*, Moscow, Nauka, 129 p. (in Russian).

Pratje O. (1932) Der Verbleib des Abbruchsmaterials der SamlandKusfe, Schr. d. phys.-okon. Geselschaft, Konigsberg.

*Processes buildup of the deposits in the Gdańsk of Gdańsk (Baltic Sea)* (1987) Edit. E. M. Emelyanov (BSSA) and K. Vupuh (PNR), Moscow, Issue AS USSR, 273 p.

Research impact of a pulp dumped in the sea on the water intakes covering of amber plant and ports of the Kaliningrad coast, The final report under the contract with Amber plant (1975) ?GU, Kaliningrad, 254 p.

Soskin I. M., Kuznetcsova L. N., Solovjev V. I. (1963) Currents of Baltic Sea on the basis of hydrological observations processing by a dynamic method, *Proceedings GOIN*, Issue 73, 76–95.

Speransky N. S. (1973) Movement of a sediment material and some features mechanical differentiation the top part of a shelf, *Oceanology*, **XIII** (5), 842–846.

Subotowicz W. (1992) Photogrammetrical estimation of modern development of the steep coasts of Poland, Studying of the basic patterns and tendencies of coastal line moving of Baltic Sea for last 100 years, Edited by Orviky K. Tallinn, 34–39.

Tidemann B. (1930) Über Wandern des Sandes Küstenraum des Samlandes, *Zeitschr. Bauw.*, (199).

Trask P. D. (1930) Mechanical analysis of sediments by centrifuge, *Econ. Geology*, pp. 25.

Zenkovich V. P. (1958) Some questions of dynamics of the Polish coast of Baltic Sea, *Proceedings UGS*, **90** (3), Moscow.