Dynamics of sediments disposed in the marine coastal zone near the Vistula Lagoon inlet, south-eastern part of the Baltic Sea

Vladimir Chechko, Andrei Sokolov, Boris Chubarenko, Dmitrii Dikii, Victoriya Topchaya

Abstract The article discusses the possibility of protecting the shore by disposing of dredged material at shallow depths. An example of a permanently eroded open marine shore segment located south of the Vistula Lagoon inlet (south-eastern part of the Baltic Sea) is considered. This shore segment is permanently caused by downstream erosion due to the moles bordering the entrance to the Vistula Lagoon (Baltiysk Strait) and interrupting longshore sediment transport. Changes of sediment distribution resulting from a demonstration disposal of clean fine sand at depths of seven to nine metres opposite the eroded segment of the shore are examined. A supplementary numerical modelling analysis of sediment transport for different winds showed that the disposed material is transported northward or southward alongshore depending on the wind direction, and almost none of it is stored at the shore slope. The demonstration disposal and numerical modelling results demonstrate that the only way to use the dredged material to protect the eroded shore near the inlet of the Vistula Lagoon is to dispose it directly onto the beach and not into the shallow water nearby.

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INTRODUCTION

Nearly all entrance moles for ports and channels in the southern and eastern parts of the Baltic Sea negatively influence the sediment dynamics along the adjacent coastline (Aibulatov, Bass 1983; Boldyrev 1988; Gudelis 1988; Basinski, Zmudzinski 1988). It is a common phenomenon that construction of hydrotechnical facilities along an open sea shore is usually followed by coastal erosion (Walker 1988; Pranzini, Williams 2013).

Entrance moles at the inlet to the Vistula Lagoon (the south-eastern part of the BalticSea) constructed at the end of the 18th century became an obstacle (Fig. 1) to the longshore sediment transport from the north to the south; consequently, the downstream coastal ero-

sion began at the shore segment immediately south of the moles. The average erosion rate at the 2.5–3 km segment of the Vistula Spit south of the moles is currently 0.7–5.5 m a year but may reach 8 m a year (Boinagryan 1966; Bass, Zhindarev 2004; Bobykina 2007). Such long-lasting permanent erosion results in a real threat of flooding for the Kosa village located south of the Baltiysk Strait (Chechko *et al.* 2008).

The southward sediment flux moves alongshore around the moles at a greater depth. In addition some of the sediments enter the Baltiysk Strait during inflow of coastal waters into the Vistula Lagoon caused by western winds (Chechko *et al.* 2008). The incoming suspended material settles down forming a reversed bar immediately within the Vistula Lagoon (Chubarenko, Margonski 2008), and reduces the depth of

the Kaliningrad Marine Canal, the navigation pass from the Baltiysk Strait to the city of Kaliningrad.

There are more than 20 offshore dumping sites (Dembska *et al.* 2012) in the south-eastern part of the Baltic Sea. It is recommended to use dredged material either for beach nourishment (Gulbinskas *et al.* 2009) or dispose it offshore in deep water (Dembska *et al.* 2012; Iotzov *et al.* 2014). Bottom sediments dredged regularly at the entrance of the Kaliningrad Marine Canal are also disposed on the official dumping site (Chechko *et al.* 2008), which is located in the open marine area 5 kilometres north of the entrance moles (Fig. 1).

This paper verifies a proposal to use the dredged material to protect the eroded shore segment at the Vistula Spit along the Kosa village following known examples of using dredged material to replace natural sediment transport processes (Boswood, Murray 2001; Schupp *et al.* 2007). In contrast to the conditions at the relatively deep dumping sites (25–30 m and 44–49 m) located near the Lithuanian shore, where material remains untouched even after extreme storms (Pupienis**,** Žilinskas 2005), the new dumping site is proposed at shallower depths of 7–9 metres, which is still safe enough for disposal operations by the dredger and allows the material to be easily re-

Fig. 1 The plan of the study area: 1 – sampling points (suspended and bottom sediments); 2 – isobaths, m; 3 – area of demonstration disposal; 4 – area of actual regular dumping; 5 – eroded segment of the shore near the Kosa village; 6 – Baltiysk Strait (the Vistula Lagoon inlet and the entrance to the Kaliningrad Marine Canal); 7 – southern and northern entrance moles; 8 – Kaliningrad Marine Canal; 9 – the area of more detailed sampling around the new dumping site

deposited shoreward by wind, waves and currents during moderate atmospheric forcing.

In 2006, a demonstration disposal was completed and was accompanied by a field study of sediment distribution before and after the disposal event. The preliminary results were not optimistic (Chechko *et al.* 2008); the numerical modelling scenario was accomplished, as it is usually performed in other studies (Cronin *et al.* 2011; Marcinkowski, Olszewski 2015**)**. The aim of this study was to analyse the results of both the field study of 2006 and the numerical simulations of the re-deposition of disposed sediments following stormy weather. The focus was on the following question: How reasonable is it to use the dredged material for local shore protection by it disposal in the marine area just opposite the eroded shore segment?
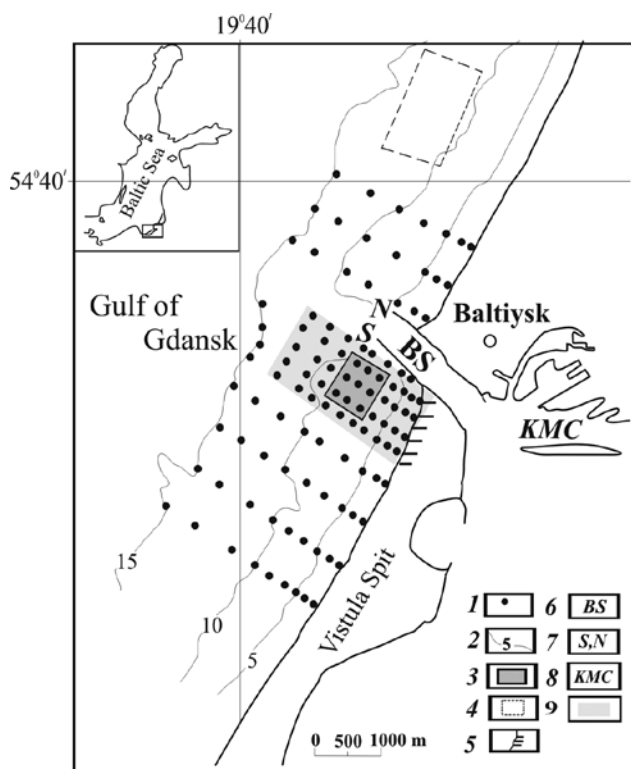
MATERIAL AND METHODS

The demonstration disposal of material in the marine area was executed southward from the southern mole at depths of 7 to 9 m just opposite the eroded segment of the shore (Fig. 1, legend 3) during the period of 17 June to 30 July 2006. The total volume of disposed material was 17000 m^3, and approximately 65% of it was disposed during the first 3 days. The dredger visited the new site several times per day and disposed of the material directly from its tanks. The disposed material was dredged from the western part of the Kaliningrad Marine Canal. It was finer than the material on the eroded segment of the shore and on the bottom slope nearby that allowed to clearly distinguish the consequences of this disposal.

The field study included two field surveys: 14–15 June 2006 and 11 July 2006 – before and 20 days after the demonstration disposal. Sediment samplings were made at 110 points located at depths of 0, 3, 5, 7, 9, 10, 11, 13 and 15 m (Fig. 1). Samples were taken from the upper sediment layer (0–10 cm) with a Peterson grab. In addition, 23 samples of disposed material were taken on board the dredger during each act of disposal.

The treatment of the samples was made by mesh and water-mechanical analysis (Petelin 1967), and revealed the following grain size grades (Wentworth 1922): coarse sand (0.5–1 mm), medium sand (0.25–0.5 mm), fine sand (0.125–0.25 mm), very fine sand (0.0625–0.125 mm), and silt (0.0625–0.039 mm). In total, 220 bottom sediment samples and 23 on-board samples were treated.

Numerical modelling[1] was completed using the MIKE model system developed at the Danish Hy-

draulic Institute (MIKE 3/21 FLOW MODEL 2004). A recent example using the same software to examine the results of dumping dredged material at sea can be found in (Marcinkowski, Olszewski 2015**).**

The computational domain (300×300 km) did not cover the entire Baltic Sea, but only part of its area. The side of this computational domain was assigned to allow wind waves to fully develop while propagating from their boundaries to the study area for the maximum winds considered in the study. Hydrodynamic simulations were made in a three-dimensional approach (10 sigma-layers in the vertical direction and an irregular spatial grid). The mesh size was 5–7 km for the main part of the domain and 10–150 m in the vicinity of the study area (Fig. 2). Bathymetry was assigned according to (Seifert, Kayser 1995). All boundaries were treated as closed boundaries. The wind was the single external force; it had uniform velocity and direction for the whole domain and was equal to the wind measured at Baltiysk. Such a model set-up showed its advantages for pure hydrodynamic simulations near the shore of the study area in (Sokolov, Chubarenko 2012).

Three modules of the MIKE numerical models system were used. The hydrodynamic module gave the solutions (water level and currents) of 3-dimensional shallow water equations, the spectral wave module (coupled with hydrodynamic module) solved the balance equation for the density of wave action (MIKE 3/21 FLOW MODEL 2004), and the sediment transport module simulated the advection and dispersion of the admixture, including its settling and re-suspension (MIKE21&MIKE3 2007). All of them were used in coupled mode.

As disposal in the marine area is undertaken during calm weather, usually when the wind does not exceed 5 m/sec, nearly all of the disposed material settles immediately at the disposal point. The material's long-shore transport is possible only in the case of a wind action when when wind waves cause re-suspension and currents will transport the material with its subsequent re-sedimentation. The intensity of erosion was estimated using the formula (MIKE21&MIKE3, 2007):

$$E = E_0 \cdot \exp(\alpha(\tau_b - \tau_c)) \qquad (1),$$

where E = the intensity of erosion of bottom sediments (kg/m^2/sec), E_0 = the erosion coefficient kg/m^2/sec), α = the power of erosion (m^2/N), τ_b = the actual bottom shear stress (N/m^2), and τ_c = the critical shear stress (N/m^2).
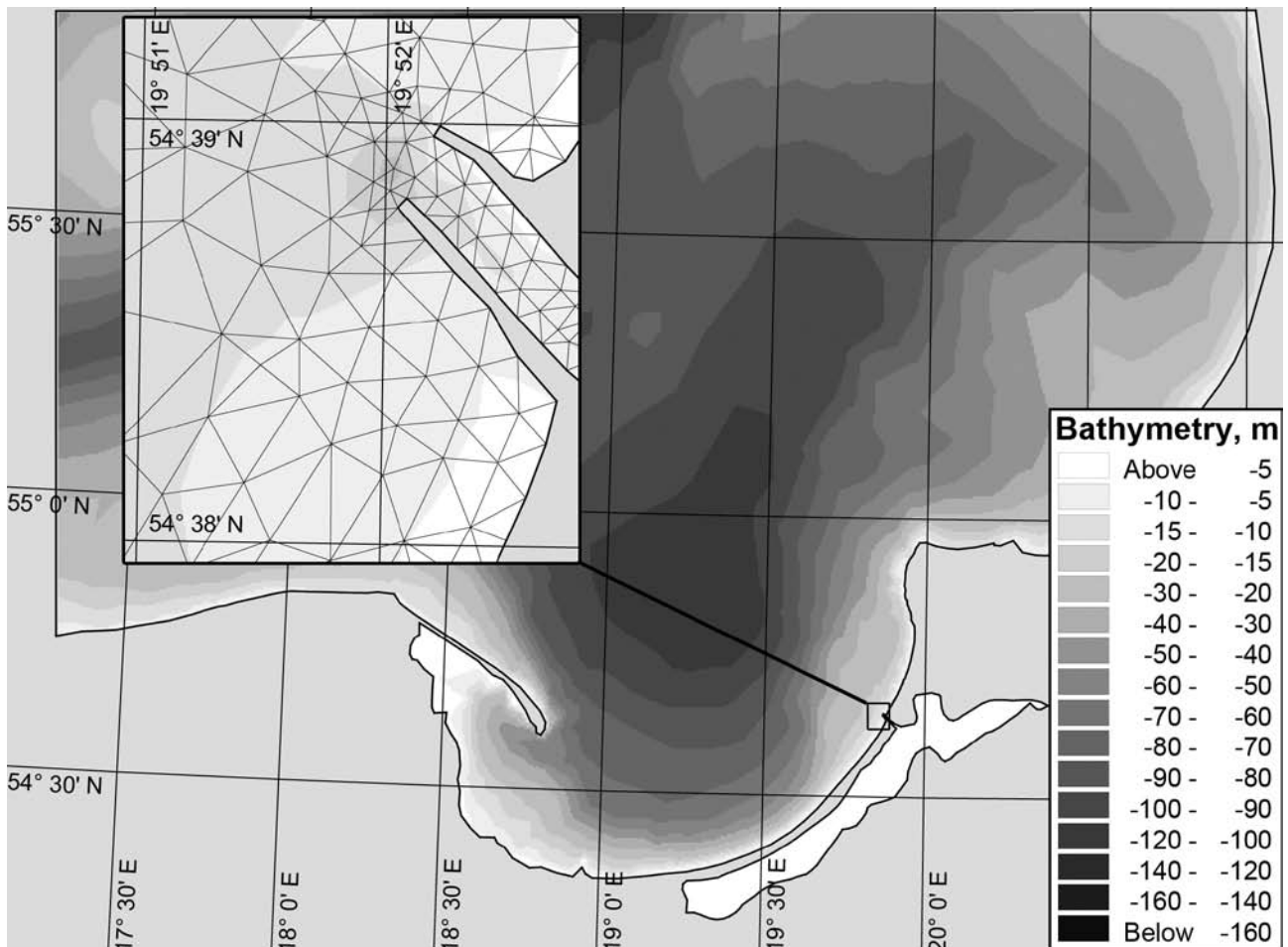

Fig. 2 Computational domain and detailed fragment of study area

MODEL CALIBRATION

The results of the calibration of the utilised model set-up of the hydrodynamic and spectral wave modules were presented in (Sokolov, Chubarenko 2012) and (Sokolov, Chubarenko 2014), respectively: the correlation coefficients between the measured and simulated currents and waves were up to 0.8, and maximal and average values were also comparable. All coefficients obtained during these studies were used in the simulations described below.

Thus, the calibration efforts in this study mostly addressed the effect of erosion parameterized by formula (1). Simulations made during the sensitivity analysis[2] showed that among the three parameters (E_0, α, τ_c), only the last, critical shear stress, is the main factor which influenced the simulation of erosion result. The following default values, $E_0 = 5 \times 10^{-5}$ kg/m^2/sec and $\alpha = 8.3$ m^2/N were assigned for future simulations, and τ_c was assigned as a calibrated parameter.

Although the value of τ_c theoretically depends on the hydraulic radius, it is not sufficient to use this theoretical formula in numerical simulations, as a correct accounting of re-suspension in numerical simulations also depends on the grid size in the vertical direction. Therefore, the simplified engineer approach was applied: the value of τ_c was estimated through calibration simulations of the erosion of the underwater bank at the demonstration disposal location. The mean diameter of the material forming the

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[2] Numerical simulations to access the development of the shape of the underwater bank due to the bottom erosion while changing the parameters in formula (1) with all other hydrodynamic characteristics remaining constant.

simulated bank was 0.07 mm, as 70% of the disposed material had this mean diameter in the studied case. The set of τ_c was tested, and for each τ_c the set of wind actions (increasing wind from zero to 20 m/sec) was simulated. Along with the wind increase, the value of the near-bottom current increased. The modelled current velocity near the top of the underwater bank was recorded when the erosion process began at the top of the bank. Thus, we obtained the relationship between τ_c and the near-bottom velocity at the moment when particles started to move in the model, i.e., the modelled critical velocity (Table 1).

According to publications (e.g., Eagleson *et al.* 1958), the critical velocity for the fine sand of 0.1 mm is 4.5–6.5 cm/sec. For the very fine sand, the critical velocity has to be less. The $\tau_c = 0.01$ N/m^2 was chosen in Table 1 as an upper limit estimation for the critical shear stress for the chosen particle diameter and thickness of the very deepest layer of the computational grid.

The model set-up with parameters obtained after calibration was used to simulate the spreading of the disposed sediments during the 20 days after disposal (14–15 June 2006). The spatial distribution of the disposed sediments agreed qualitatively with the real distribution revealed by the second field survey on 11 July 2006; the re-deposited material was cross-shore elongated, the maximum thickness was a little more than 20 cm, and the area covered by re-deposited material was less than that measured in the field.

Model simulations included scenarios of different wind forcing to analyse the possible re-deposition of the disposed material. Considering that the north, north-west and south-west winds repeat most fre-
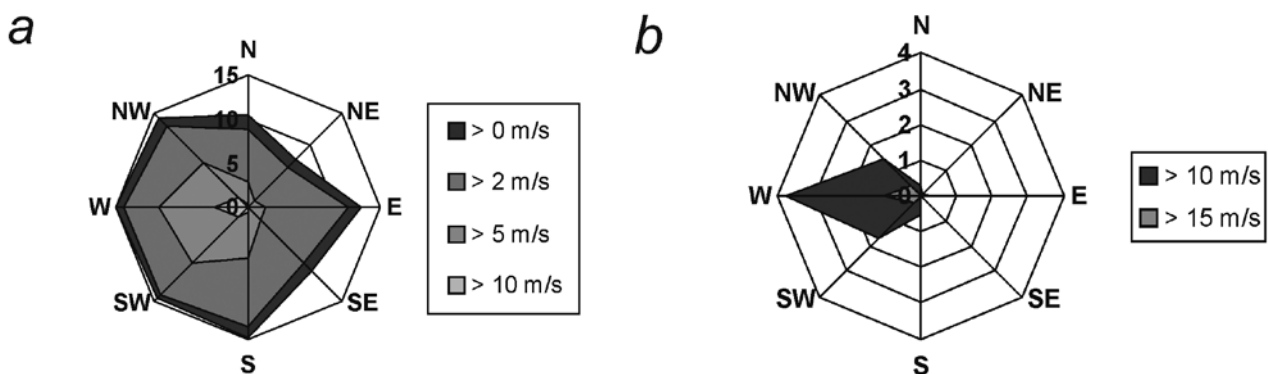
Fig. 3 Repeatability (%) of wind directions for all winds, data for Baltiysk, 1947–1988, in a form of 'nested wind roses' per wind speed grades: (a) – grades 'higher than' 2, 5 and 10 m/sec, (b) – grades 'higher than' 10 and 15 m/sec. Compiled by B. Chubarenko using data from the Russian Hydrometeorological Service

Table 1 Results of the calibration simulations of erosion of an underwater bank at the demonstration disposal location under increasing wind forcing.

	0.01	0.02	0.03	0.04
Value of critical shear stress τ_c (N/m^2), assigned for the model set–up	0.01	0.02	0.03	0.04
Near–bottom current (cm/sec) when bottom particles (Ø = 0.07 mm) started to move at the top of the sediment bank	4.3	5.7	6.7	7.5

quently for wind grades higher than 10, 15, 20 and 25 m/sec (Fig. 3), the scenarios were limited by two wind directions: north and north-west winds. These are two alternative wind actions, as winds from these directions repeat most frequently and cause longshore currents in completely different directions (see the results section). The time variation of the wind forcing applied in the model was assigned as a step function (Fig. 4) with a wind duration of 24 hours. Wind magnitudes were 10, 15, and 20 m/sec. The final distribution of the disposed material was analysed at moment D, 24 hours after the end of the wind action (Fig. 4).

RESULTS

Samples of disposed sediments (23 samples) taken aboard the dredger, showed that the disposed material contained 62–75% (71% in average) of very fine sand, with admixtures of the fine sand (15–23%, 19% in average), medium sand (4–9%, 7% in average), coarse

Fig. 4 Temporal wind forcing variations for modelling simulations: period of disposal of material and its settling (A–B), one-day period of wind (B–C), time for settling of material following the wind action (C–D)
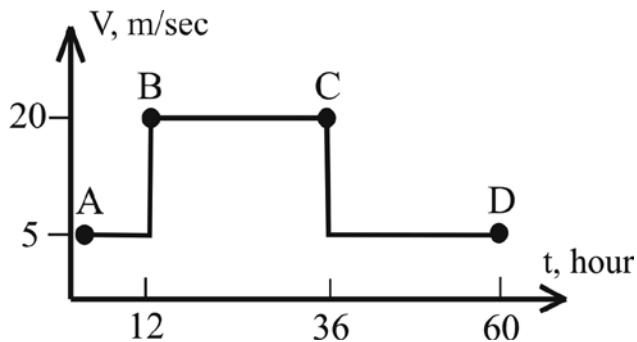
sand (0.2–0.7%, 0.5% in average) and silt (0.8–2.4%, 2% in average).

Survey made on 14–15.06.2006 before the demonstration disposal in the marine area. Analysis of the background bottom sediment distribution showed the domination of the fine sand (Ø = 0.25–0.1 mm) and the medium sand (Ø = 0.5–0.25 mm) in the area north and south of the entrance moles (from the coastal line to depths of 15 m). In general, the fine sands were predominant on the bottom slope from the depths to the coastline, and the strip of medium sands was found near the coastline only at the shore segments adjacent to the moles (Fig. 5). Another area of medium sand was found at a depth of 10 m to the south of the moles.

Fine-grained sediments were well sorted (the sorting coefficient averaged 1.32) and had a high-mass content of fine sand particles (75–88%). The admixture of medium sand might reach 23% of the weight of the sample. The content of very fine sand did not exceed 2% of the sample weight. The absolute domination (97%) of the fraction of fine sand was found only in some samples taken north of the moles.

The probes, which were classified as medium sand sediments, were not as well sorted, and the sorting coefficient varied between 1.40 and 2.18. The content of the predominant fraction, medium sand, was 53%–82%. Fine sand was the main admixture in these samples, with the share of very fine sand not less than 1%.

The control survey of sediment sampling, 11 July 2006. The thickness of the layer of disposed sediments (approximately 15 cm) in the centre of the new dumping site was estimated by bore hole sampling. The control sediment sampling showed that the
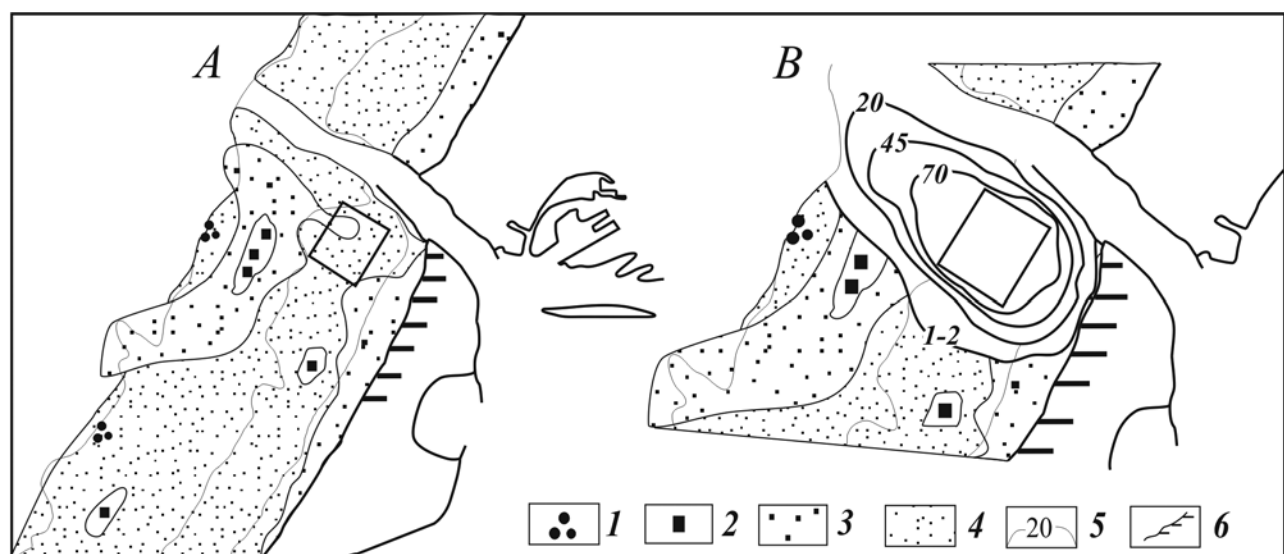
Fig. 5 Spatial distribution of the bottom sediments (upper layer 0–10 cm) in the study area (a) just before the experimental disposal (Chechko *et al.* 2008, with extension) and (b) 20 days after the disposal: 1 – gravel with pebbles; 2 – coarse sand; 3 – medium sand; 4 – fine sand; 5 – isolines of the content (%) of very fine sand in the sediments; 6 – eroded segment of the shore

content of the upper bottom sediment layer changed significantly after the disposal event, not only at the site of disposal but also in the surrounding area. Tables 2 and 3 contain the data of the grain size analysis of samples in the selected area around the new disposal site located 1 km south of the entrance moles at a depth of 13 m (Fig. 1).

The fine sand previously found over a rather large area was covered by very fine sand after the demonstration disposal. A maximum content (70%) of very fine sand was revealed at the disposal site. It meant that the upper bottom layer was partly eroded during the period before the control survey and the disposed material was re-deposited, forming an oval-shape zone with its main axis perpendicular to the shoreline (Fig. 5).

It is important to note that very fine sand particles were found at a greater distance from the disposal site towards the deeper areas than in the shallows. Thus, at the shoreline (1000 m from the disposal site) no very fine sand was found at all, while its content was 4–12% at any sampling point at a depth of 15 metres (more than 1800 m from the disposal site).

### Results of simulation of wind action scenarios

Winds of 10 m/sec initiate only partial erosion of the bottom-disposed load, and a considerable amount of the disposed material remains where it was deposited. Modelling results showed the major sensitivity of the spreading pattern of disposed material to be due to changes in the wind direction. Currents near the shore differ considerably for winds from the western and north-western directions (Fig. 6). For westerly winds the current in the study area is directed northwards[3], while it is directed southwards for north-westerly winds. The large difference between the spatial distributions of re-deposited material for north-westerly and westerly winds (wind speed 10 m/sec) is illustrated in Fig. 7. After a north-westerly wind, the layer of disposed material still retained its thickness of 10 to 13 cm, but a large plume of the very thin layer shows that spreading of eroded material is directed to the south. For the westerly wind, the thickness at the disposal site drops to 3 cm, material is transported northward, and part of this material is even deposited within the Baltiysk Strait (Fig. 7b).

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[3]   We do not discuss the curious collision between the fact that for the water area near the Baltiysk Strait, on the one hand, the resulting longshore sediment flux is directed southwards according to all geomorphological indications, and on the other hand, westerly winds and the northward currents following them (as shown here by the modelling) predominate in the study area. The hypothesis one can formulate is that the cause of the southward longshore sediment flux is the action of strongest waves coming in during north-westerly and northerly storms.

Table 2 Grain size composition (in %) in the samples taken on 14–15.06.2006 (before the demonstration disposal) in the selected area (the shadow area 9 on the Fig. 1) around the site of demonstration disposal. Results are averaged for selected depths (0, 3, 5, 6, 7, 8, 9, 10, 11, 13 m). Limits of range and an average value are indicated as numerator and denominator

Depth, m	Number of samples	Grain size, mm						Md, mm (median diameter)	So (sorting)
		2–1	1–0.5 (coarse sand)	0.5 –0.25 (medium sand)	0.25–0.125 (fine sand)	0.125–0.063 (very fine sand)	0.063–0.05 (silt)		
0	4	–	$\frac{0.4–0.7}{0.55}$	$\frac{76–82}{79}$	$\frac{17–23}{20}$	$\frac{0.3–0.5}{0.4}$	–	$\frac{0.3–0.41}{0.36}$	$\frac{1.16–1.25}{1.2}$
3	5	–	$\frac{0.3–0.6}{0.4}$	$\frac{26–78}{55}$	$\frac{21–72}{44}$	$\frac{0.4–1.2}{0.8}$	–	$\frac{0.2–0.33}{0.26}$	$\frac{1.2–2.2}{1.46}$
5	5	–	$\frac{0.3–0.7}{0.5}$	$\frac{24–78}{44}$	$\frac{21–74}{54}$	$\frac{0.4–1.0}{0.7}$	–	$\frac{0.2–0.32}{0.24}$	$\frac{1.25–2.1}{1.4}$
6	4	–	$\frac{0.3–0.7}{0.5}$	$\frac{26–72}{47}$	$\frac{26–73}{51}$	$\frac{0.6–1.0}{0.8}$	–	$\frac{0.19–0.29}{0.24}$	$\frac{1.31–2.1}{1.5}$
7	5	–	$\frac{0.3–0.4}{0.35}$	$\frac{22–45}{29}$	$\frac{54–70}{69}$	$\frac{0.6–1.4}{1.2}$	–	$\frac{0.18–0.23}{1.19}$	$\frac{1.25–1.4}{1.3}$
8	5	–	$\frac{0.3–0.5}{0.4}$	$\frac{19–54}{31}$	$\frac{74–77}{76}$	$\frac{0.7–1.7}{1.2}$	–	$\frac{0.17–0.2}{0.18}$	$\frac{1.19–1.25}{1.22}$
9	5	–	$\frac{0.5–0.8}{0.65}$	$\frac{23–59}{36}$	$\frac{40–75}{65}$	$\frac{0.6–1.4}{1.0}$	–	$\frac{0.18–0.27}{0.21}$	$\frac{1.2–2.2}{1.5}$
10	5	–	$\frac{0.5–1.2}{0.8}$	$\frac{21–69}{43}$	$\frac{29–77}{55}$	$\frac{0.7–1.4}{1.1}$	–	$\frac{0.18–0.29}{0.23}$	$\frac{1.25–1.44}{1.36}$
11	5	–	$\frac{1.3–63}{26}$	$\frac{28–58}{36}$	$\frac{5–70}{38}$	$\frac{0.3–0.6}{0.4}$	–	$\frac{0.19–0.57}{0.36}$	$\frac{1.29–2.4}{1.9}$
13	5	–	$\frac{0.7–72}{29}$	$\frac{25–63}{42}$	$\frac{4–65}{29}$	$\frac{0.3–0.8}{0.6}$	–	$\frac{0.22–0.63}{0.4}$	$\frac{1.4–2.3}{1.8}$
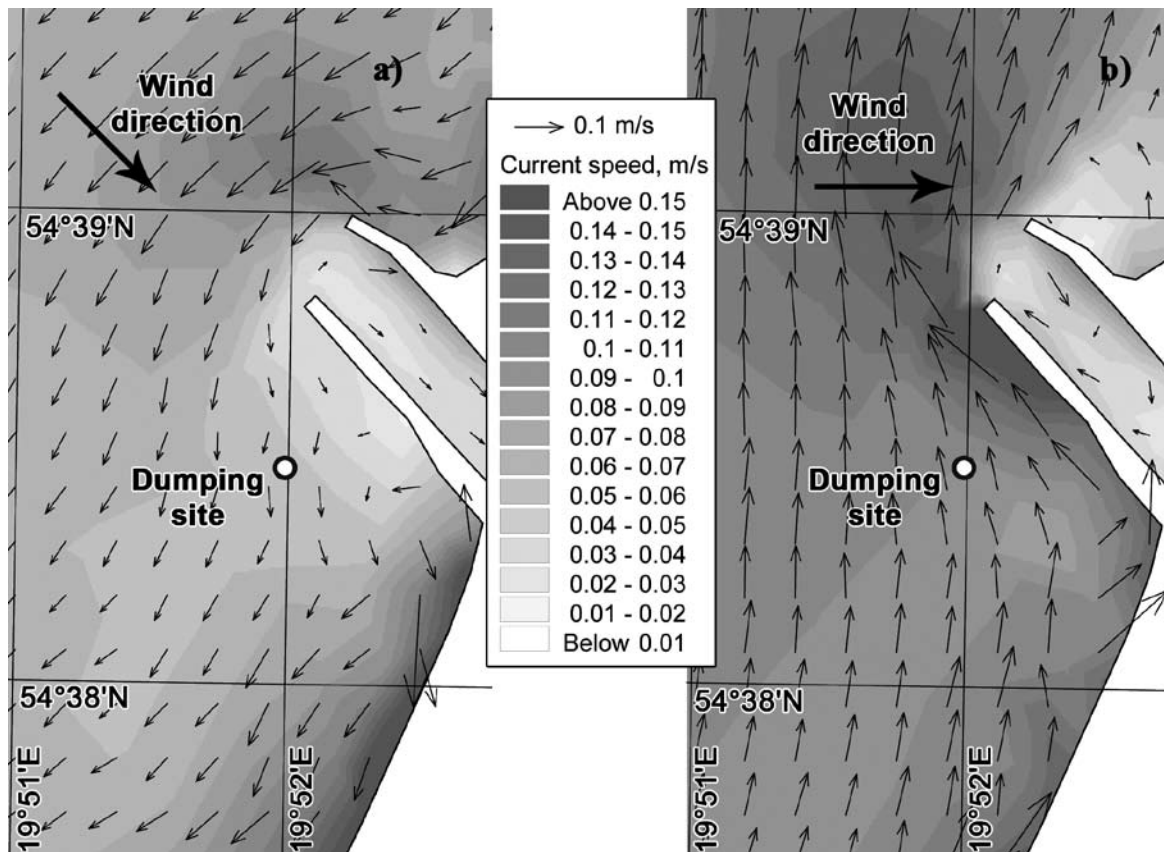
Fig. 6 Currents at the study area under the influence of a wind speed of 10 m/sec from the (a) north-western and (b) western directions

Table 3 Grain size composition (in %) in the samples taken on 11.07.2006 (after the demonstration disposal) in the selected area around the site of demonstration disposal (the shadow area 9 on the Fig. 1). Results are averaged for selected depths (0, 3, 5, 6, 7, 8, 9, 10, 11, 13 m). Limits of range and an average value are indicated as numerator and denominator

Depth, m	Number of samples	Grain size, mm						Md, mm (median diameter), mm	So (sorting)
		2–1	1–0.5 (coarse sand)	0.5–0.25 (medium sand)	0.25–0.125 (fine sand)	0.125–0.063 (very fine sand)	0.063–0.05 (silt)		
0	4	–	$\frac{0.4–0.7}{0.55}$	$\frac{75–82}{78.5}$	$\frac{16–23}{19.5}$	$\frac{1.5–2.1}{.8}$	–	$\frac{0.3–0.41}{0.36}$	$\frac{1.16–1.25}{1.2}$
3	5	–	$\frac{0.2–0.7}{0.4}$	$\frac{24–70}{49}$	$\frac{14–71}{36}$	$\frac{5–19}{14}$	–	$\frac{0.18–0.29}{0.24}$	$\frac{1.35–1.5}{1.51}$
5	5	–	$\frac{0.2–0.5}{0.3}$	$\frac{10–66}{29}$	$\frac{11–55}{34}$	$\frac{22–46}{35}$	$\frac{0.3–1.2}{0.9}$	$\frac{0.13–0.29}{0.17}$	$\frac{1.4–1.72}{1.55}$
6	4	–	$\frac{0.3–0.6}{0.4}$	$\frac{7–55}{27}$	$\frac{20–41}{26}$	$\frac{24–69}{53}$	$\frac{0.6–1.3}{1.1}$	$\frac{0.11–0.29}{0.16}$	$\frac{1.39–2.3}{1.73}$
7	5	–	$\frac{0.3–0.4}{0.35}$	$\frac{4–19}{10}$	$\frac{19–62}{33}$	$\frac{34–71}{56}$	$\frac{1.2–2}{1.5}$	$\frac{0.07–0.17}{1.12}$	$\frac{1.2–1.46}{1.34}$
8	5	–	$\frac{0.2–0.3}{0.25}$	$\frac{8–12}{9}$	$\frac{17–42}{28}$	$\frac{48–72}{62}$	$\frac{0.5–1.4}{0.9}$	$\frac{0.07–0.13}{0.1}$	$\frac{1.2–2.4}{1.7}$
9	5	–	–	$\frac{6–23}{11}$	$\frac{18–70}{32}$	$\frac{18–73}{55}$	$\frac{1.3–2}{1.6}$	$\frac{0.07–0.17}{0.11}$	$\frac{1.2–1.8}{1.35}$
10	5	–	$\frac{0.4–0.8}{0.6}$	$\frac{3–54}{16}$	$\frac{17–54}{34}$	$\frac{17–71}{50}$	$\frac{0.7–1.5}{1.1}$	$\frac{0.07–0.25}{0.14}$	$\frac{1.2–2.3}{1.71}$
11	5	–	$\frac{53–59}{22}$	$\frac{9–30}{15}$	$\frac{6–69}{27}$	$\frac{5–67}{36}$	$\frac{1–1}{1}$	$\frac{0.12–0.56}{0.3}$	$\frac{1.4–2.3}{2.1}$
13	5	–	$\frac{0.7–67}{27}$	$\frac{16–27}{19}$	$\frac{4–65}{27}$	$\frac{2–50}{27}$	$\frac{0.6–0.7}{0.3}$	$\frac{0.21–0.62}{0.36}$	$\frac{1.43–2.5}{2.0}$

In the model the bank of disposed material was fully eroded by currents caused by a wind of 15 m/sec. The principle[4] patterns of sediment distribution for two wind directions are presented in Fig. 8. For wind from the north-east, the suspended material is transported southwards along the shore; it may be re-deposited in a large area of 50 km² at a considerable distance from the shoreline. The deposition area has the shape of an ellipse stretched along the shoreline; the distance between the disposal point and the centre of the area covered by re-deposited material is approximately 10 km. For westerly winds, the disposed material is spread around a huge area to the north and deposited at a distance of tens of kilometres from the disposal site. The part of transported material trapped by the Baltiysk Strait settled deeper in the lagoon and the Kaliningrad Marine Canal area.

North-westerly and westerly winds of 20 m/sec ensure a much greater spreading of the disposed material than winds of 15 m/sec, and the material re-deposits widely around the study area.

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[4] The tiny thickness of the sediment layer calculated by the model should not be considered as a practical forecast, but rather an indication of areas where material may be re-deposited.

DISCUSSION

Concerning the weather conditions, from the first three days of the demonstration disposal until the control survey (17 June–11 July 2006), the wind speed averaged 2–4 m/sec during this period, with a few exceptions when winds achieved 6–7 m/sec for 3–6 hours. These events occurred on the following dates: 27 June 2006 – wind from the south-east and the east-north-east; 30 June 2006 – northerly wind; 10 July 2006 – wind from the east-north-east. Eastern winds of the same magnitude (also three short periods from 17 June to 11 July 2006) were not considered as the disposal point is in the leeward zone of southerly and easterly winds.

The control survey 20 days after disposal showed that the fill of disposed material was considerably eroded under the action of the three events mentioned above. The very fine deposited sand particles completely covered the disposal site area. The disposed material spread mostly in two directions – toward the deepest areas and shoreward. It was not re-deposited at the nearest segment of shoreline, although the wind conditions seemed to be favourable for that.

Notably, most of the material was washed out to greater depths, rather than to the shore; moreover, no
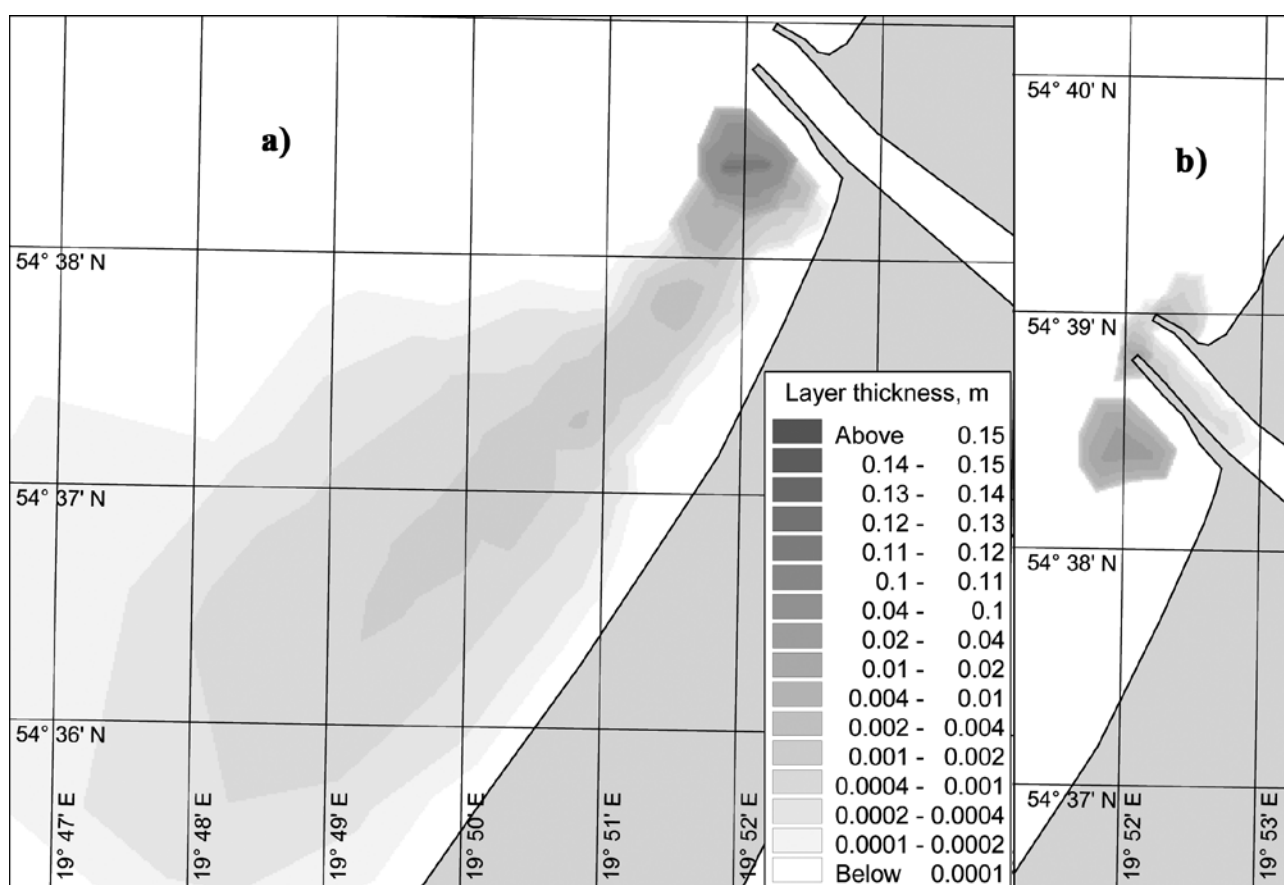
Fig. 7 Spatial distribution of disposed material on the bottom after a one-day action of wind at 10 m/sec from the (a) north-western direction and (b) western direction

increase of the very fine sand faction was found at the shoreline. The proportion of very fine sand in a sample equalled 70% at the disposal site (depths of 7–9 m), 45% at the depth of 5 m and 20% at the depth of 3 m. At the shoreline, where the medium sand prevails, the share of very fine sand was the same as before the disposal (not more than 1% of the sample). Consequently, the sediments disposed at the shallow depth opposite the eroded segment of the shore did not reach this segment.

The numerical simulations of stronger wind scenarios also supported this conclusion. Model simulations showed that the transport of a minor part of the disposed material to the eroded segment of the shoreline is possible only for a north-easterly wind of approximately 10 m/sec. The main part of the disposed material does not remain at the disposal site, but is re-deposited to the south-west, forming a plume with a maximum concentration approximately 500 m from the shoreline (Fig. 7). When winds of the same magnitude blow from the west, no replacement of suspended disposed material to the shore takes place; its flux is directed towards the moles and to the northeast along the shore. For stronger winds, when the disposed bank is completely eroded, no re-deposition of even a part of the disposed material to the shore was showed by simulations; all re-suspended material was transported along the shore for distances of tens of kilometres from the disposal site.

Despite active coastal erosion processes, no material accreted on the underwater slope (Boinagryan 1966; Bass, Zhindarev 2004; Bobykina 2007) south of the entrance moles. The field study and modelling revealed that the bank of disposed material being formed in this area would be eroded very quickly even under moderate wind conditions. This is in agreement with the statement that a hydrodynamic mechanism exists at the area south of the moles, which permanently washes out sediments from the bottom slope (Chechko et al. 2008).

According to Aibulatov and Bass (1983), longshore sediment transport prevails at the western shore of the Sambian Peninsula and cross-shore transport is weakly developed. However, this is not true for the area south of the entrance moles of the Vistula Lagoon. These moles are perpendicular to the shoreline and together with the shoreline itself form a 'corner'. The wind-induced water level set-up, established within this corner during winds from western quarter, causes an intense and compensating near-bottom flow directed seawards. In other words, the moles are the stressor which changes the natural situation and forms intensive cross-shore, near-bottom fluxes, which do not allow sand accumulation to develop on the bottom slope and to change the existing equilibrium profile.

Material transported by these fluxes is entrained in the longshore current, with the magnitude and di-
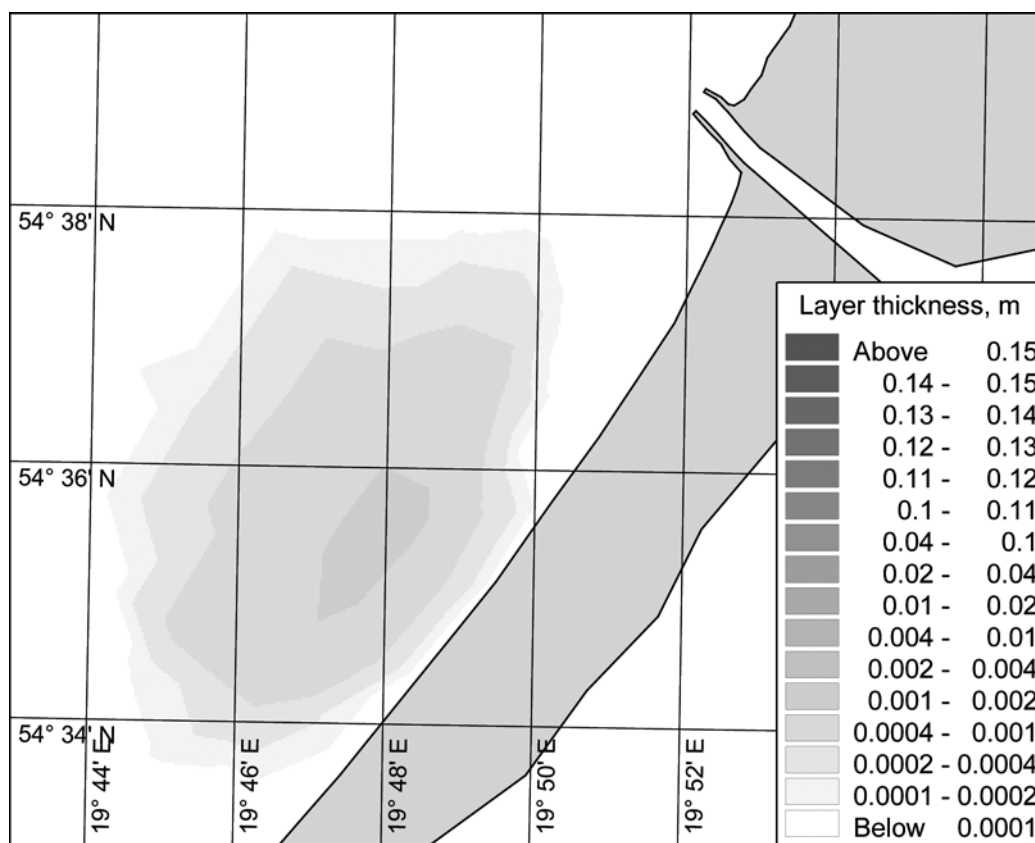
Fig. 8 Spatial distribution of disposed material after the one-day action of the north-westerly wind of 15 m/sec.

rection determined by the wind – the longshore flow goes to the northeast for westerly winds and to the southwest for north-westerly winds. The main part of the disposed sediments is very quickly transported out either deeper or alongshore for long distances from the disposal site.

Therefore, the material disposed at the site located at a depth of 7–9 m (safe for disposal operations by the dredger) in the vicinity of the moles to their south and just opposite the eroded shore segment cannot be beneficial for the stability of the shoreline. In addition, numerical simulations showed that this material may be partly trapped within the Baltiysk Strait, i.e., it returns back to the place where it was dredged.

This was not addressed here, but the following recommendation may be made: sandy sediments dredged in the Kaliningrad Marine Canal can be used to protect the shoreline south of the entrance moles by disposing of it on the beach near the core part of these moles. Once ground-based slurry pipe-lines are deployed across the core part of the southern entrance mole, the dredged material may be pumped to the eroded shore segment from the dredger safely located within the area between the entrance moles.

Taking the average rate of coastal erosion in the studied area as 2–4 m a year and considering the bottom slope at 8 m depths as stable, one may estimate that for 1 linear kilometre of the shoreline the volume of sediments which should be restored equals 0.5*[2 or 4] m*8 m*1000 m = 8000 or 16000 m^3 of material. The annual volume of dredging in the Kaliningrad Marine Canal is approximately 5–10 times higher.

As medium sand prevails at the shoreline (see Table 2), medium or coarse sand should be used for beach nourishment. Considering that the portion of medium sand is approximately 7% of the total dredged volume, one may conclude that disposing of the dredged material during beach nourishment can compensate, in general, for the loss of sediments and diminish further coastal erosion of the studied segment of the shore.

CONCLUSIONS

The field study of the redistribution of the very fine sand disposed at the proposed new dumping site demonstrated that the primary part of the disposed material was transported seaward by currents caused by winds of magnitude less than 7 m/sec blowing from the western quarter. The disposed material transported towards the shore did not reach the shoreline.

Numerical modelling did not reveal onshore transport but exhibited its re-deposition along the shore depending on the wind direction: for north-western winds – to the south; and for western winds – to the north of the new dumping site.

The entrance moles of the Baltiysk Strait, which project into the sea, cause upwind compensating near-bottom currents in the area south of the moles, which do not allow movable sand material eroded from the shoreline to accumulate on the bottom slope. It means that the proposed beach nourishment must be regular. Estimation of the annual losses of materials at the bottom slope south of the entrance moles indicates 8000–16000 m^3 a year per 1 linear kilometre of shoreline. The same amount of medium or coarse sands is needed to compensate for this loss.

The proposal to place dredged material offshore opposite the eroded shore segment of the Vistula Spit, even at the shallow depth of 6 to 7 m, was found not to be applicable. An alternative suggestion was formulated to dispose the dredged material directly onto the shoreline.

In general, the examined example demonstrates that protection of a shore by the disposal of sediments in the marine area near the eroded shore segment is not highly effective in the case of downstream erosion behind a cross-shore construction located at the open sea shore. Coastal erosion typically manifested by shoreline retreat is supported by washing out sediments from the bottom slope, and this mechanism will permanently negate the effect of disposal.

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