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# Numerical simulation of dynamics of sediments disposed in the marine coastal zone of the south-eastern Baltic

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**Abstract**. Three dumping sites located at the south-eastern part of the Baltic Sea at shallow depths near the shore of the Sambian Peninsula are considered. The first and second ones are located south and north of the Vistula Lagoon inlet, and are used now for disposing dredged material extracted from the Kaliningrad Seaway Canal. The third dumping site is located near the northern shore of the Sambian Peninsula, east of Cape Gvardeyskiy and assigned for disposing the dredged material extracted from the fairway to the Pionerskiy Port located nearby. All three dumping sites are located either in front of or not far from the eroded segments of the shore. The question behind the study is: Is it possible that disposed material is naturally transported from the damping site to the shore and accumulates there to protect it from erosion? A numerical hydrodynamic transport 3D model (MIKE) was used to model sediment transport under different wind actions. The winds with the speed stronger than 15 m/s wash out disposed material completely from the dumping site and spread it over a wide area with a negligible layer thickness. Winds of about 7–10 m/s transport material along the shore at a distance of a few kilometres; that may be useful for shore protection. Winds with a speed of about 5 m/sec or less do not lead to resuspension of sediments. The first location of the dumping site looks very ineffective for potential protection of the shore nearby. On the other hand, the second and especially the third locations are favourable for the transport of disposed material to the shore; the most favourable conditions are at onshore or alongshore currents.

***Keywords*** *• dumping • sediment transport • numerical simulation • wind waves • near shore currents*

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## INTRODUCTION

It is known (Aibulatov, Bass 1983; Basinski, Zmudzinski 1988; Boldyrev 1988) that the entrances to marinas and ports in the south-eastern Baltic are regularly being filled with sand and therefore require periodic dredging. On the other hand, construction of any port on the open sea shore usually negatively influences the sediment balance in the location, and coastal erosion very often becomes a problem after port construction. The idea to use the damped material for coastal protection in the south-eastern Baltic was introduced in (Boldyrev 1999), but was not implemented, and therefore the recommendations (Gulbinskas *et al*. 2009) are still actual. This issue was not addressed by previous studies. The fundamental DYNOS Project activities (Harff *et al*. 2009), during which the depositional processes in the natural and anthropogenically influenced environment of the south-western Baltic Sea were modeled, covered many aspects of the processes of erosion, transport and deposition of sedimentary material and their interrelation with the benthic components of the ecosystem. This paper continues the DYNOS approach of computerised modelling of depositional processes and analysis of dumping sites in the Baltic Sea.

One of the places at the shoreline of the Sambian Peninsula (south-eastern Baltic) demanding constant deepening is the inlet of the Vistula Lagoon, the Strait of Baltiysk (Fig. 1), which hosts the main fairway connecting ports of Kaliningrad with the Baltic Sea. Entrance moles bounding this inlet from the marine side are obstacles for alongshore sediment transport, and coastal erosion exists just south of the moles at a distance of 2.5–3 km (Chechko *et al*. 2008, 2015). In June 2006, an experimental dumping of dredged materials was carried out in the vicinity of the eroded shore (inset of Fig. 1, site 1). Disposed material was transported seawards and landwards in equal proportions, and evident signals of strengthening of the shore at the Kosa Village, located opposite the dumping site 1, were absent. Detailed results of field measurements and numerical simulations were presented in (Chechko *et al*. 2015). The results showed that the disposed material is transported along the shore and cannot reach the shoreline under any landward wind conditions. It was concluded that the only effective suggestion which could strengthen the coast is to dispose dredged material directly onto the beach.

Dumping sites 2 and 3 (Fig. 1) are used regularly nowadays to dispose the dredged material. The dumping sites 1 and 2 (inset in Fig. 1) are for the material dredged in the Strait of Baltiysk: site 1 was opened in 2017 as a reserved one, while site 2 has been used

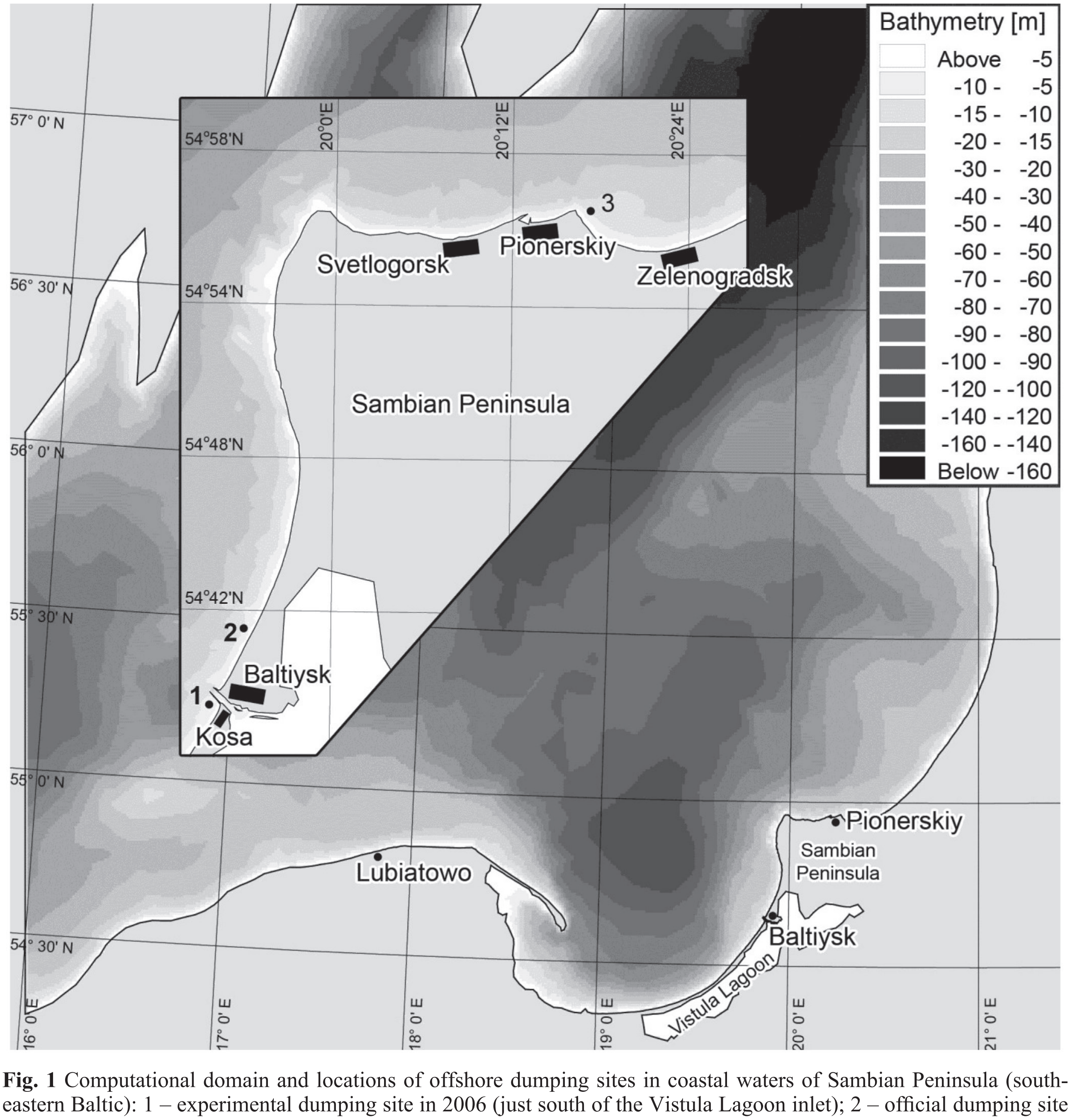

**Fig. 1** Computational domain and locations of offshore dumping sites in coastal waters of Sambian Peninsula (south-eastern Baltic): 1 – experimental dumping site in 2006 (just south of the Vistula Lagoon inlet); 2 – official dumping site for dredged material from the Vistula Lagoon inlet; 3 – official dumping site for dredged material from the Pionerskiy Port

regularly for decades. The dumping site 3 is used to accumulate dredged material after the deepening of the fishery port near the town of Pionerskiy. There is a plan to develop this port before the beginning of the FIFA World Cup 2018. Consequently, the dumping site 3 will be intensively used in the future.

A typical procedure of dredging and disposing is as follows: A pump transports material from a deepening point (the bottom of a channel, for example) to a barge. Then the barge goes to a dumping site, where it unloads. The unload procedure lasts about 15–20 minutes: flaps open in the bottom of the barge and suspended material goes out of the barge and gradually settles on the bottom. The exact location of deposition depends on the hydrometeorological conditions during the discharge: the speed and direction of the wind, waves and currents, as well as the relief of the bottom and the depth at which the discharge occurs. In addition, the behaviour of the dumped material also depends on its characteristics: size of particles, their tendency to stick together, and so on.

Generally, the procedure of dredging and disposing is conducted in calm weather, usually when the wind speed does not exceed 3–5 m/sec. In this situation, the dumped material settles down to the bottom not far around the disposal point. The further transportation of the deposited material is possible only under the influence of wind and waves. Namely, the wind must produce waves that can cause resuspension of sediments.

In the paper, we consider the situation after the deposition, when the deposited material is still not consolidated on the bottom (not much time after the dumping event). What will happen if the wind blows from a certain direction with a certain speed?

The aim of the current study is to simulate the dynamics of sediments settled on the dumping sites 1, 2, and 3 and resuspended by the consequent wind. In particular, the investigation should show situations when the dredged material could be transported alongshore and serve to protect some part of the shore from erosion[1]. The paper presents a "what-if" scenario analysis and is based on numerical simulations.

## METHODS

### 1. Numerical formulation

Simulations were performed using the software package MIKE developed by DHI Software (MIKE 2017a, 2017b, 2017c). A three-dimensional formulation (10 layers in depth, sigma-coordinate) was used for simulations. The computational domain covered the central part of the Baltic Proper, 350 × 350 km (Fig. 1). The depth field was taken from the digital topography of the Baltic Sea (Seifert, Kayser 1995). Mesh sizes of irregular grid were about 5–7 km for the open sea, and about 100 m in the vicinity of the dumping sites. All boundaries of the computational domain were closed, and wind was the only driving force in the model. It was assumed that wind measured in Baltiysk could be uniformly applied to the entire area of simulations. Such a model setup showed its advantages for coupled hydrodynamic and wind waves simulations near the shore of the study area in (Sokolov, Chubarenko 2012, 2014).

The simulations used three modules working in the coupled mode.

The ***Hydrodynamic Module*** gives the solutions (water level and currents) of 3-dimensional shallow water averaged Navier-Stokes equations (MIKE 2017a):

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=S, \tag{1}$$

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial vu}{\partial y}+\frac{\partial wu}{\partial z}=fv-g\frac{\partial \eta}{\partial x}-\frac{1}{\rho_0}\frac{\partial p_a}{\partial x}-$$
$$-\frac{g}{\rho_0}\int_z^{\eta}\frac{\partial \rho}{\partial x}dz+F_u+\frac{\partial}{\partial z}\left(v_t\frac{\partial u}{\partial z}\right)+u_sS\,, \tag{2}$$

$$\frac{\partial v}{\partial t}+\frac{\partial v^2}{\partial u}+\frac{\partial uv}{\partial y}+\frac{\partial wv}{\partial z}=-fu-g\frac{\partial \eta}{\partial y}-\frac{1}{\rho_0}\frac{\partial p_a}{\partial y}-$$
$$-\frac{g}{\rho_0}\int_z^{\eta}\frac{\partial \rho}{\partial y}dz+F_v+\frac{\partial}{\partial z}\left(v_t\frac{\partial v}{\partial z}\right)+v_sS. \tag{3}$$

Here, $t$ is the time; $x$, $y$, and $z$ are the Cartesian coordinates; $\eta$ is the surface elevation; $u$, $v$, and $w$ are the velocity components in the $x$, $y$, and $z$ direction; $f$ is the Coriolis parameter; $g$ is the gravitational acceleration; $\rho$ is the density; $\rho_0$ is the reference density; $p_a$ is the atmospheric pressure; $v_t$ is the vertical turbulent (or eddy) viscosity; $F_u$ and $F_v$ are the horizontal stress terms; $S$ is the magnitude of the discharge due to point sources; and $(u_s, v_s)$ is the velocity by which the water is discharged into the ambient water.

The ***Spectral Wave Module*** is based on a wave action density balance equation (MIKE 2017b):

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}c_xN+\frac{\partial}{\partial y}c_yN+\frac{\partial}{\partial \omega}c_\omega N+\frac{\partial}{\partial \theta}c_\theta N=\frac{S}{\omega}\cdot \tag{4}$$

Here, $N$ is the action density; $t$ is the time; $x$ and $y$ are the Cartesian co-ordinates; $\theta$ is the wave direction; $\omega$ is the relative (intrinsic) angular frequency.

The first term in the left-hand side of this equation represents the local rate of change of action density in time. The second and the third terms represent the

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[1] The present study includes and extends significantly the work partly reported only in Russian (Sokolov, Chubarenko 2017).

propagation of action in geographical space (with propagation velocities $c_x$ and $c_y$ in $x$- and $y$-space, respectively). The fourth term represents the shifting of the relative frequency due to variations in depths and currents (with propagation velocity $c_\omega$ in ω-space). The fifth term represents depth-induced and current-induced refraction (with propagation velocity $c_\theta$ in θ-space).

The energy source term, $S$, represents the superposition of source functions describing various physical phenomena:

$$S = S_{in} + S_{nl} + S_{ds} + S_{bot} + S_{surf}. \qquad (5)$$

Here, $S_{in}$ represents the generation of energy by wind; $S_{nl}$ is the wave energy transfer due to non-linear wave-wave interaction; $S_{ds}$ is the dissipation of wave energy due to whitecapping; $S_{bot}$ is the dissipation due to bottom friction; and $S_{surf}$ is the dissipation of wave energy due to depth-induced breaking.

The ***Mud Transport Module*** simulates the advection and dispersion of the admixture, including its settling and resuspension (MIKE 2017c):

$$\frac{\partial c}{\partial t}+u\frac{\partial c}{\partial x}+v\frac{\partial c}{\partial y}+w\frac{\partial c}{\partial z}=$$

$$=\frac{\partial}{\partial x}\left(D_x\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y\frac{\partial c}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_z\frac{\partial c}{\partial z}\right)+S. \qquad (6)$$

Here, $c$ is the mass concentration; $t$ is the time; $x$, $y$, and $z$ are the Cartesian co-ordinates; $u$, $v$, and $w$ are the flow velocities; $D_x$, $D_y$, and $D_z$ are the dispersion coefficients; $S$ is source/sink term. This term depends on whether the local hydrodynamic conditions cause the bed to become eroded or allow deposition to occur.

## 2. Calibration and verification

The calibration of the model was performed using field data of 01.10–22.11.2006 collected by the Institute of Hydro-Engineering of the Polish Academy of Sciences (IBW PAN) (Pruszak *et al*. 2008). Current speed and direction were recorded by the Acoustic Doppler Current Profiler installed about 200 meters from the shore opposite the Lubiatowo Field Station of IBW PAN (see Fig. 1). Depth at the point of installation was about 4–4.4 meters. The ADCP measured current velocities at 0.4 and 2.4 meters above the bottom. Wind data were recorded by an automatic meteorological station installed at the Lubiatowo Field Station of IBW PAN. Wave parameters were recorded by a wave buoy installed opposite the field station at a depth of 15 m. The results of the model setup calibration for currents (*Hydrodynamic Module*) and waves (*Spectral Wave Module*) were presented in (Sokolov, Chubarenko 2012) and (Sokolov, Chubarenko 2014), respectively. The correlation coefficients between the measured and simulated currents (speed and direction) and wave parameters (significant wave height and peak wave period) were up to 0.8, and their maximal and average values were also comparable.

The model setup used in the study is based on the simplified assumption that wind speed and direction in the computational area are uniform (Soomery 2001). Arguments behind are as follows: 1) satellite data (OSWT) show that wind speed and direction over the Baltic Sea can be considered almost the same within the regions with a characteristic size from hundreds to thousands of kilometres; 2) the previous simulations (Sokolov, Chubarenko 2012, 2014) showed a good agreement between field measured and simulated results for waves and currents while based on

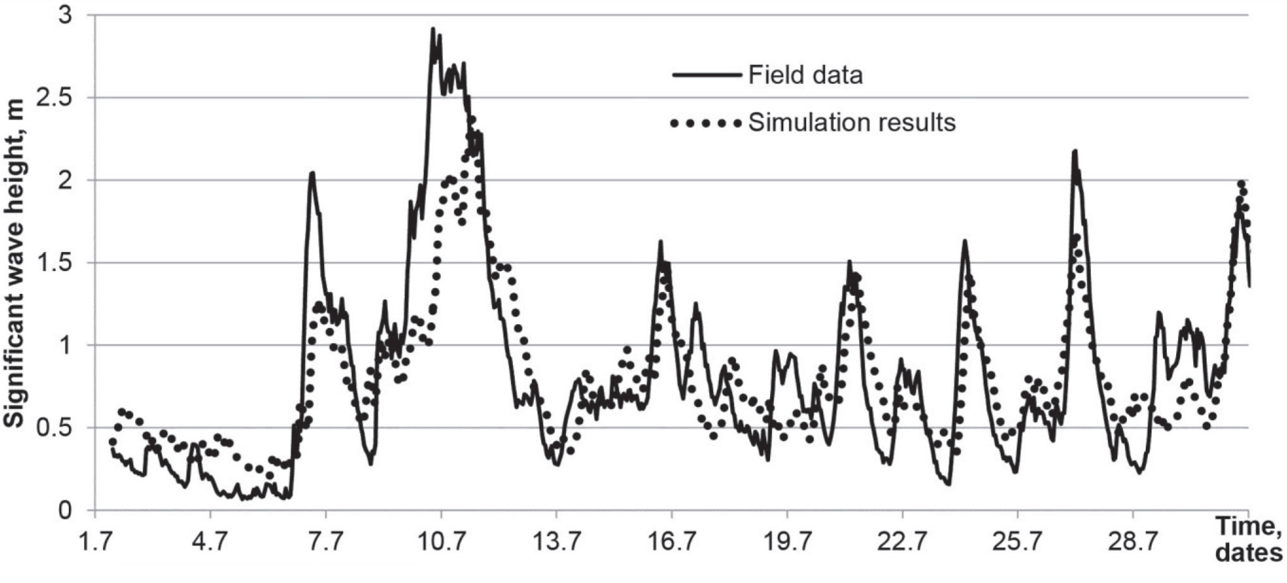

**Fig. 2** Significant wave height (field measurements and simulations) in July 2015. The solid line represents field data obtained by the wave buoy installed at a depth of 15 m opposite Lubiatowo Field Station of IBW PAN (Poland). The dotted line represents simulation results performed under atmospheric forcing based on wind speed and direction measured in Baltiysk, located 200 kilometres east from the field station

the same assumption (Fig. 2). The solid line in Fig. 2 represents field data obtained by the wave buoy of the IBW PAN for the period of 01–31.07.2015 installed at a depth of 15 m. The dotted line represents simulation results. Simulations were performed for the point where the buoy was located but applied wind speed and direction were taken from measurement at the meteorological station located in Baltiysk more than 200 kilometres far from Lubiatowo. In this case a good coincidence between field data and simulation results (correlation coefficient is higher than 0.8) shows that the assumption of wind uniformity over the computational area is quite acceptable for simulations of hydrodynamic parameters not far from the point of wind measurements.

The calibration of parameters of the *Mud Transport Module* was based on the field data obtained in the field experiment conducted in June 2006 (Chechko *et al*. 2008) at the dumping site 1 (see inset in Fig. 1). The measurements of particle size distribution were conducted for bottom sediments around the dumping site 1 before and after the discharge of about 17000 m$^3$ of dredged material with 70% of quartz sand with a median diameter of 0.07 mm. The measurements showed that a sediment spot was formed after the discharge and it was stretched along the southern entrance mole, then the average thickness of the bed layer of the sediments was 15 cm. Related model parameters defining the settling and resuspension properties of the particles were the following: the settling velocity according to the Stocks formula was 0.004 m/s; critical shear stress for erosion was taken as 0.01 N/m$^2$. Simulations reproduced the conditions of the field experiment, the calculated bed layer thickness was 17 cm and the calculated sediment distribution at the bottom was similar to the observed distribution (see details in Chechko *et al*. (2015)). All coefficients obtained during calibration were used in the simulations described below.

This calibration procedure does not allow to make a general parametrization of settling velocity and critical shear stress for material of different grain size. The idea of the calibration was to find calibration parameters (in a line of DYNAS (Harff *et al*. 2009; Bobertz *et al*. 2009 ) approach to use bottom roughness and critical shear stress as model calibration parameters) but exactly for quartz sand with a median diameter of 0.07 mm.

### 3. Model setup for dumping scenarios

This paper presents the results of simulations of dumping events at all three dumping sites mentioned above. The amount of the discharged material in the model scenarios was 17000 m$^3$ (as in the experimental dumping of 2006 on site 1). The dumping event lasted 20 minutes, i.e. the source with discharge of 14 m$^3$/s was assigned at the top computational sigma-layer. The depth of the sea at the dumping site locations was very similar: 8.1 m at dumping site 1; 8.8 m at dumping site 2; 8.8 m at dumping site 3.

First, the model simulated the settling of sediments on the bottom and formation of some spot of the deposits around the place of dumping, and then these sediments were resuspended by waves and transported by currents farther from the dumping site. Model scenarios of constant wind action (32 in total) were simulated: the wind of 5, 7, 10, and 15 m/sec blew from 8 main directions: N (0°), NE (45°), E (90°), SE (135°), S (180°), SW (225°), W (270°), and NW (315°).

The wind speed varied during the scenario (duration is 72 hours) as follows: it started at a rate of 3 m/sec (for all scenarios) and was constant within 12 hours from the beginning of the scenario. After that, the dumping event occurred (20 minutes) but the wind speed remained 3 m/sec for another 12 hours. Then the speed increased instantly up to the wind rate of the scenario and remained constant within 24 hours. After that a period of "calm" weather started, i.e. the wind speed dropped instantly to 3 m/ sec (for all scenarios) and stayed constant within 24 hours. So, it was assumed that some spot of the sediments initially forms at the bottom immediately after disposal, and resuspension of this material occurs only after increasing of the wind speed. After spreading, sediments are settled down during the "calm" period. The wind direction did not change within the scenario. The wind speed of 3 m/s was selected due to the fact that this is the middle of wind interval for the period of a favourable weather when most dumping works are conducted.

## RESULTS

### 1. Dumping site 1

Winds of 5 m/sec. The winds blowing from S, SW, and W lead to resuspension but the initial spot of sediments deforms slightly. The resuspended sediments move seaward not far from the initial spot. The winds from other directions do not lead to resuspension and the initial spot of sediments does not deform.

Winds of 7 m/sec. The winds blowing from NE, E, and SE do not lead to resuspension and the initial spot of sediments does not deform. The winds blowing from other directions lead to resuspension and partial erosion of the initial spot of sediments. The winds blowing from N and NW affect the initial spot slightly and sediments are transported not far from the initial spot (Fig. 3 a). The winds blowing from

S, SW, and W affect the initial spot significantly and sediments are transported for distances of about 10 or more kilometres (Fig. 3b). In some cases, sediments go back to the Vistula Lagoon inlet, where dredging is being conducted (Fig. 3b).

Winds of 10 m/sec. The wind blowing from E does not lead to resuspension and the initial spot of sediments does not deform. The winds blowing from NW, N, and SE affect the initial spot slightly and sediments are transported seaward not far from the initial spot, similar to the situation shown in Fig. 3a. The winds blowing from W, SW, and S affect the initial spot significantly and sediments are transported for distances up to several tens of kilometres. The most interesting is the NE situation (Fig. 4). In this case, the resuspended sediments are transported alongshore for a distance of about several kilometres and, in contrast to previous cases, the sediments are transported not seaward but landward (Fig. 4b). The upwelling effect can be seen here: velocities in the bottom layer are directed to the shore (Fig. 4a). This situation is positive from the point of view of coastal protection as the sediments from the dumping site could settle to the shore nearby and enlarge the beach.

Winds of 15 m/sec. The wind blowing from SE affects the initial spot slightly and sediments are transported seaward not far from the initial spot, similar to the situation shown in Fig. 3a. The winds blowing from NW, N, and NE affect the initial spot significantly and sediments are transported seaward for distances up to several tens of kilometres. The winds blowing from S, SW, and W completely wash out the initial spot and spread the sediments across huge distances where the sediment layer thickness is negligible. The E situation looks similar to the NE situation with the wind speed of 10 m/sec. In this case, the resuspended sediments are transported alongshore for a distance of about several kilometres landward, so that they could settle to the shore and strengthen the beach.

## 2. Dumping site 2

Winds of 5 m/sec. The winds blowing from E and SE do not lead to resuspension and the initial spot of sediments does not deform. The winds from other directions lead to resuspension but the initial spot of sediments deforms slightly. In most cases resuspended sediments move seaward not far from the initial spot. In the case of the NE wind, the resuspended sediments move landward, and they can settle to the shore nearby and strengthen the beach.

Winds of 7 m/sec. The wind blowing from SE does not lead to resuspension and the initial spot of sediments does not deform. The winds from other directions lead to partial resuspension of sediments and deforming of the initial spot. The winds blowing from W and NW affect the initial spot slightly and sediments are transported seaward up to several kilometres from the initial spot. The winds blowing from N, SW, and S affect the initial spot significantly and sediments are transported seaward for distances

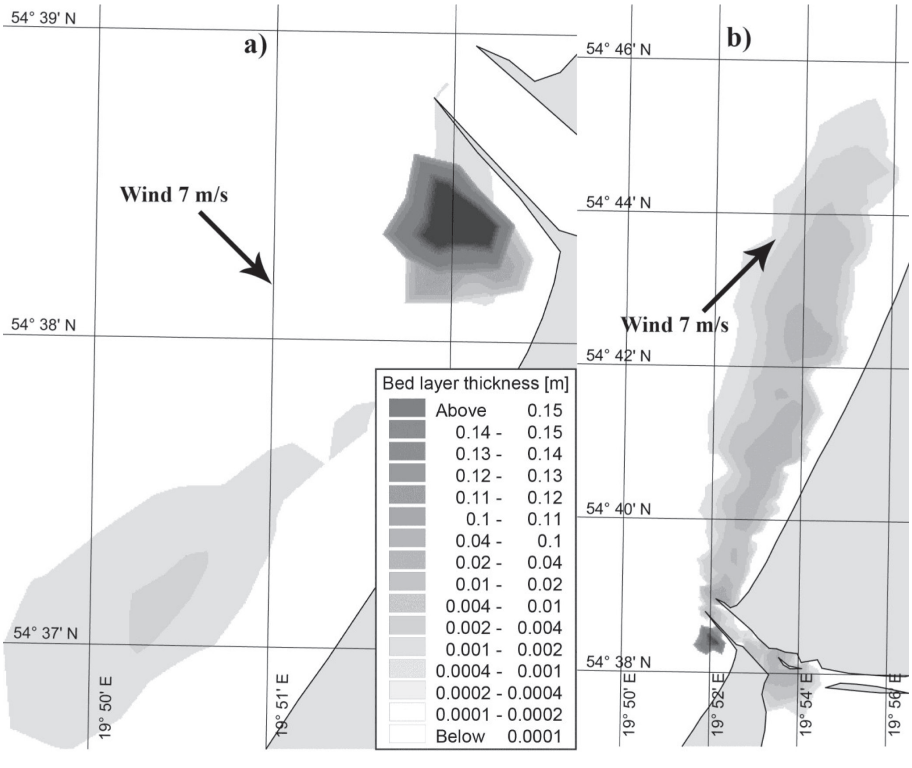

**Fig. 3** Bed layer thickness of sediments deposited at the dumping site 1 for the scenario cases of north-west (315°, a) and south-west (225°, b) winds with the maximum speed of 7 m/s

of about 10 or more kilometres. The winds blowing from N and NE affect the initial spot slightly and sediments are transported landward (Fig. 5a) that can enlarge the beach.

Winds of 10 m/sec. The winds blowing from E and SE affect the initial spot slightly and sediments are transported landward that can enlarge the beach. The winds blowing from S, W, NW, and NE affect the initial spot significantly and sediments are transported for distances up to several tens of kilometres. In most cases, the sediments move seaward, but under the NE wind – landward (Fig. 5b). The winds blowing from N and SW completely wash out the initial spot and spread the sediments across huge distances where the sediment layer thickness is negligible.

Winds of 15 m/sec. The winds blowing from E and SE affect the initial spot significantly and sediments are transported alongshore for distances from several to tens of kilometres. The sediments are transported landward, can settle to the shore and enlarge the beach, but due to a long distance from the initial spot the sediment layer thickness is very small. The winds blowing from other directions completely wash out the initial spot and spread the sediments across

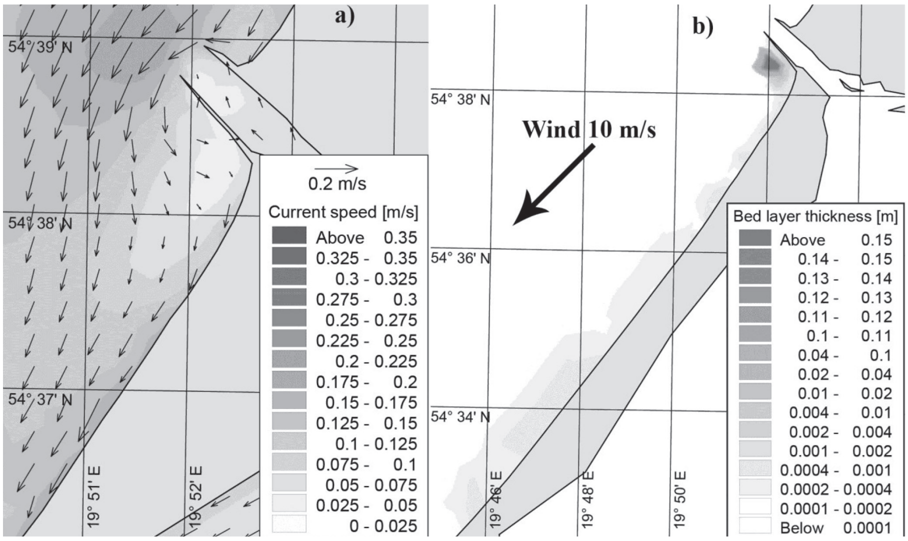

**Fig. 4** The scenario case of north-east (45°) wind with the maximum speed of 10 m/s (for the dumping site 1): (a) the bottom currents at the end of wind action period and (b) the bed layer thickness of sediments redistributed from the dumping site

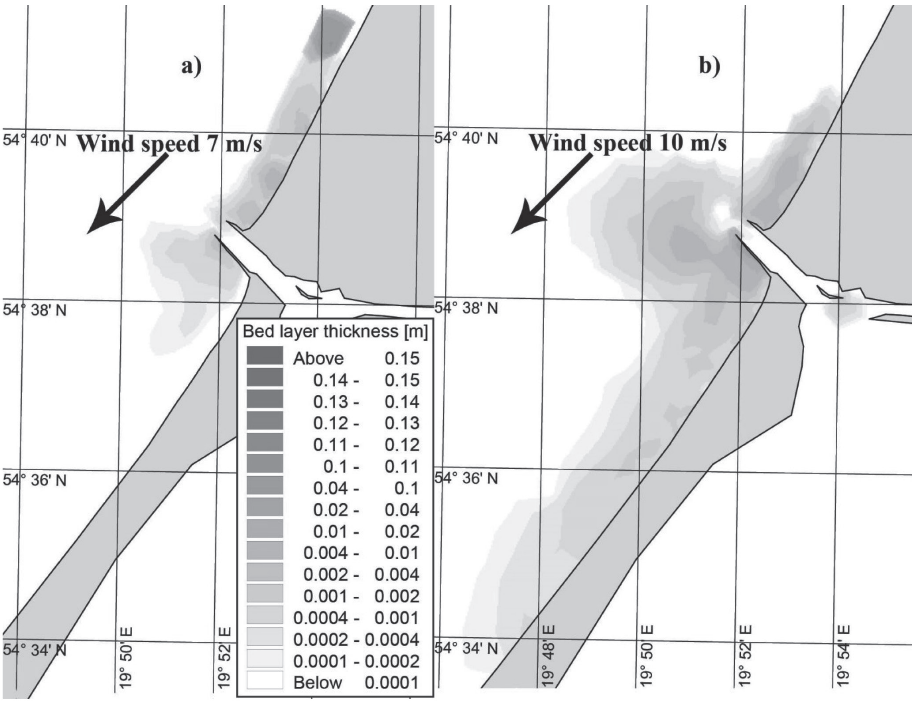

**Fig. 5** Bed layer thickness of sediments deposited at the dumping site 2 for the scenario cases of north-east (45°) wind with the maximum speed of 7 m/s (a) and 10 m/s (b)

huge distances where the sediment layer thickness is negligible.

## 3. Dumping site 3

Winds of 5 m/sec. The winds blowing from SE, S, SW, and N do not lead to resuspension and the initial spot of sediments does not deform. The winds blowing from W, NW, E, and NE lead to resuspension but the initial spot of sediments deforms slightly. In the case of W and NW winds, the resuspended sediments move seaward not far from the initial spot. In the case of the E and NE winds, the resuspended sediments move landward, settle to the shore nearby and can enlarge the beach.

Winds of 7 m/sec. The wind blowing from S does not lead to resuspension and the initial spot of sediments does not deform. The winds from other directions lead to partial resuspension of sediments and deforming of the initial spot. The winds blowing from SW, W, NW, and N affect the initial spot slightly and sediments are transported seaward. The winds blowing from NE (Fig. 6a), E, and SE affect the initial spot slightly and sediments are transported landward that can enlarge the beach.

Winds of 10 m/sec. The winds blowing from SW (Fig. 6c) and SE affect the initial spot slightly and sediments are transported landward that can enlarge the beach. The winds blowing from N (Fig. 6b) and S affect the initial spot slightly and sediments are transported seaward. The winds blowing from W, NW, NE, and E affect the initial spot significantly and sediments are transported for distances up to tens of kilometres. In the case of W (Fig 6d) and NW winds, the sediments move seaward, and in the case of NE and E winds – landward.

Winds of 15 m/sec. The wind blowing from S affects the initial spot slightly and sediments are transported seaward. The wind blowing from N affects the initial spot significantly and sediments are transported seaward for a distance of several tens of kilometres. The winds blowing from other directions completely wash out the initial spot and spread the sediments across huge distances where the sediment layer thickness is negligible.

## DISCUSSION

The information what can happen with deposited sediments for all possible cases of wind speed and directions is summarized in Table 1. The first two columns contain information of a probability of a specific wind, which could help to estimate the statistical significance of the situation.

It can be seen that even winds with a speed of 5 m/ sec in some cases lead to resuspension of the sediments deposited at a depth of 8–9 m. It means that orbital velocities near the bottom generated by the wind waves are strong enough to resuspend and move the settled sediments. It is logical that directions of the winds which can produce waves strong enough depend on the coastline configuration. In particular, the southern protective mole of the Strait of Baltiysk and the coastline of the Vistula Spit act as a shield against wind waves and currents for dumping site 1. As a consequence, we see that only 3 wind directions lead to resuspension at dumping site 1, while for damping sites 2 and 3 there are 5 and 4 favourable wind directions, respectively. It should be noticed that the influence of a 24 hour 5 m/sec wind on the initial spot of the sediments is very slight in all cases. The layer thickness of the initial spot of the sediments does not change more than 5% under any wind directions.

Moderate winds (7–10 m/sec) may affect the initial spot in a wide range: from slight to significant deformation and up to complete wash out. The result depends on the wind direction and orientation of a

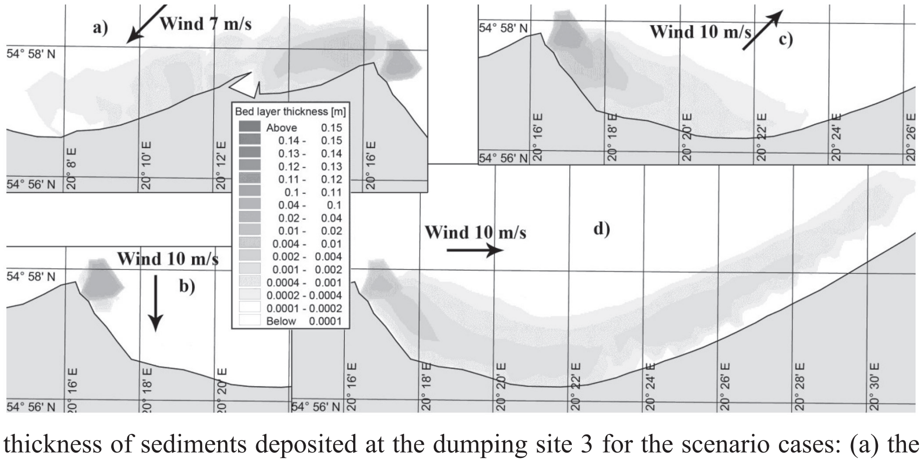

**Fig. 6** Bed layer thickness of sediments deposited at the dumping site 3 for the scenario cases: (a) the north-east (45°), wind speed 7 m/s; (b) from the north (0°, 10 m/s); (c) from the south-west (225°, 10 m/s), and (d) from the west (270°, 10 m/s)

**Table 1.** The fate of the sediments disposed at the dumping sites after the influence of different winds. “0”: the initial spot of the sediments does not deform; “No”: the initial spot of the sediments deforms slightly, resuspended sediments are transported seaward; “Yes”: the initial spot of the sediments deforms slightly, resuspended sediments are transported landward; “Far”: the initial spot of the sediments deforms significantly, resuspended sediments are transported very far from the dumping site; “∞”: sediments are washed out from the dumping site completely and spread across the huge area, the layer thickness is negligible

| Wind range | Probability, % | Modelled wind speed | Dumping site 1 | Dumping site 2 | Dumping site 3 |
|---|---|---|---|---|---|
| SW, 2–5 m/s | 5.16 | SW, 5 m/s | No | No | 0 |
| SW, 6–9 m/s | 7.19 | SW, 7 m/s | Far/No | Far/No | No |
| SW, 10–13 m/s | 1.38 | SW, 10 m/s | Far/No | ∞ | **Yes** |
| SW, 14–17 m/s | 0.24 | SW, 15 m/s | ∞ | ∞ | ∞ |
| W, 2–5 m/s | 4.01 | W, 5 m/s | No | No | No |
| W, 6–9 m/s | 6.38 | W, 7 m/s | No | No | No |
| W, 10–13 m/s | 2.76 | W, 10 m/s | Far/No | Far/No | Far/No |
| W, 14–17 m/s | 0.74 | W, 15 m/s | ∞ | ∞ | ∞ |
| NW, 2–5 m/s | 6.04 | NW, 5 m/s | 0 | No | No |
| NW, 6–9 m/s | 5.55 | NW, 7 m/s | No | No | No |
| NW, 10–13 m/s | 1.06 | NW, 10 m/s | No | Far/No | Far/No |
| NW, 14–17 m/s | 0.3 | NW, 15 m/s | Far/No | ∞ | ∞ |
| N, 2–5 m/s | 5.97 | N, 5 m/s | 0 | No | 0 |
| N, 6–9 m/s | 2.54 | N, 7 m/s | No | Far/No | No |
| N, 10–13 m/s | 0.22 | N, 10 m/s | No | ∞ | No |
| N, 14–17 m/s | 0.06 | N, 15 m/s | Far/No | ∞ | Far/No |
| NE, 2–5 m/s | 5.44 | NE, 5 m/s | 0 | **Yes** | **Yes** |
| NE, 6–9 m/s | 1.01 | NE, 7 m/s | 0 | **Yes** | **Yes** |
| NE, 10–13 m/s | 0.03 | NE, 10 m/s | **Yes** | Far/**Yes** | Far/**Yes** |
| NE, 14–17 m/s | < 0.01 | NE, 15 m/s | Far/**Yes** | ∞ | ∞ |
| E, 2–5 m/s | 9.46 | E, 5 m/s | 0 | 0 | **Yes** |
| E, 6–9 m/s | 1.62 | E, 7 m/s | 0 | **Yes** | **Yes** |
| E, 10–13 m/s | 0.3 | E, 10 m/s | 0 | **Yes** | Far/**Yes** |
| E, 14–17 m/s | < 0.01 | E, 15 m/s | **Yes** | Far/**Yes** | ∞ |
| SE, 2–5 m/s | 6.87 | SE, 5 m/s | 0 | 0 | 0 |
| SE, 6–9 m/s | 2.14 | SE, 7 m/s | 0 | 0 | **Yes** |
| SE, 10–13 m/s | 0.01 | SE, 10 m/s | No | **Yes** | **Yes** |
| SE, 14–17 m/s | < 0.01 | SE, 15 m/s | No | Far/**Yes** | ∞ |
| S, 2–5 m/s | 7.78 | S, 5 m/s | No | No | 0 |
| S, 6–9 m/s | 5.34 | S, 7 m/s | Far/No | Far/No | 0 |
| S, 10–13 m/s | 0.48 | S, 10 m/s | Far/No | Far/No | No |
| S, 14–17 m/s | 0.04 | S, 15 m/s | ∞ | ∞ | No |

shoreline near the location of the dumping site. The resuspended sediments may be transported away from several to several tens of kilometres. The direction of the transport may be seaward and landward depending on the wind direction and orientation of the shoreline. It is easy to see that landward transport occurs (‘Yes’ and ‘Far/Yes’ cases in Table 1) only under wind actions with a seaward component: NE and E for the dumping site 1; NE, E, and SE for the dumping site 2; and SW, NE, E, and SE for the dumping site 3. Our simulations show that in these cases, currents generated by winds have a noticeable component in the bottom layer that is oriented towards the shore. For other wind directions, a seaward component of currents dominates and no deposition along the shore is expected. In all cases when the wind causes a coastal upwelling, the landward transport is expected. The upwelling itself is developing at some distance seaward from the shoreline (Esiukova *et al*. 2014), but the lateral strip of water near the shore traps sediments resuspended from the dumping site.

Quite unusual is the dynamics of resuspended sediments at the dumping site 3 under SW wind. When the wind speed is 5 m/sec, the sediments are transported seaward, but when the wind speed is 7 m/sec, the sediments are transported landward. The reason is linked with directions of currents in a bottom layer: in the case of 5 m/sec, no landward component is observed, but in case of 7 m/sec, the upwelling situation occurs and the landward component appears.

A landward transport of the resuspended sediments is favourable for potential enlargement of the beach and protection of the shore. It is especially important for the dumping site 1 located near the constantly eroded shore in front of the Kosa village (see insert in Fig. 1). It was shown (Chechko *et al*. 2015) that no landward wind action brings sediments from dumping site 1 to the shore opposite it, and therefore the beach near the Kosa village is not protected by the disposal of dredged material to this dumping site. The simulation of NE wind made in the current study showed that bottom currents are directed landward (Fig. 4a), while the currents in the top layer are oriented mainly along the shore and a little bit seaward. This causes resuspended sediments to spread along the shore of the Vistula Spit and settle down along 10 km from the dumping site. In modelling simulations, we obtained that near-bottom currents are able to transport the particles of 0.07 mm. The same result was reported in (Golenko *et al*. 2016) by comparison of POM modelling results with the Hjulstrom diagram.

To compare the dumping sites from the point of view of potential efficiency to protect the nearest shore from erosion, we summarized probabilities of the relevant winds and obtained that for the dumping site 1 less than 1% of all the time of a year is favourable, for the dumping sites 2 and 3 favourable periods occupy about 10% and more than 20% of a year, respectively. If we eliminate weak winds (with a speed less than 5 m/s), when material does't spread from the dumping site, only about 5% of the year for the dumping site 2 and about 7% for the dumping site 3 become favourable for intensive transport of damped material to the shore. This clearly explains why the shore in front of the Kosa village is constantly eroded (Chechko *et al*. 2015) and the efficient protection of this part of the shore can be provided only by disposing the dredged material directly onto the beach.

It should be noticed that moderate winds in the same cases may transport the resuspended sediments back to the places where the sediments were dredged, i.e. the Strait of Baltiysk or the port near the town of Pionerskiy. See examples in Fig. 3b and Fig. 7a. Sediments can even come into the Vistula Lagoon, which is quite unusual. These facts should be taken into account when the discharge event is being planned, and situations of SE wind in the nearest future should be avoided.

Simulations showed that for all dumping sites which have similar depth (8–9 m), strong winds (more than 15 m/sec) blowing for about 24 hours completely wash out the initial sediment spot at the dumping site and spread sediments to such a wide area that thickness of the layer after subsequent deposition is negligible (Table 1). So, only the winds in the range of 5–15 m/sec may be favourable for redepositing sediments from the dumping sites to the nearest segments of the shore.

## CONCLUSIONS

Winds with a speed of about 5 m/sec or less do not lead to resuspension of sediments at the dumping sites located at the depths of about 8–9 m. Winds with a speed more than 15 m/sec lead to the complete washing out of the disposed material from the dumping site and spread it over a wide area with a negligible layer thickness.

If we consider the dumping sites located at the depths of 8–9 m from the point of view of coastal protection, the best option are the winds with velocities of the order of 7–10 m/s, under certain conditions, up to 15 m/s, which wash out the disposed material and transport it along the shore at a distance of a few kilometres. The possibility of transferring material to the shore depends on a favourable combination of several factors: wind speed, its direction, coast stretch, and its configuration. In general, disregarding the shore direction, the most favourable is an upwelling situation when velocities of currents in the bottom layer have a component directed to the shore.

For the dumping sites located at the western shore of the Sambian Peninsula (site 1 and site 2) the winds with alongshore (southward) and seaward components may transport sediments towards the shore. But the probability of such winds is very insignificant: no more than 5% during the year, and even 1% for the dumping site 1. This means that the most practical way to use the dredged material for coastal protection is its disposal directly to the shoreline, even if this method is more expensive than the disposal in the marine environment. On the other hand, it should be mentioned that dumping may diminish the quality of beaches for touristic purposes as suspended matter may be spilled to the shore.

For the dumping site at the northern shore of the Sambian Peninsula (site 3), the probability of winds favourable for onshore transport is higher and reaches 7%. The location of the dumping site 3 is more practically suitable for supporting the nearest shore by sediments disposed there, but even in this case the probability of favourable winds is still very small. So, beach protection vie duping in the water is possible, but looks not so efficient as direct dumping on the beach.

Finally, we should note that the interpretation of the results is based on plausibility conclusions only and that filed experiments are to be recommended for practical application.

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