Assessment of the potential for dredged material dispersal from dumping sites in the Gulf of Gdańsk

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Abstract

Purpose Environment-friendly management of sites used for disposal of locally generated sedimentary material involves designation of an optimal dumping site location which will render the dredged material re-usable for beneficial purposes. The objective of this research was to determine whether wind, waves, and currents can induce transport of sediment from offshore dumping sites located at intermediate depths in the southern Baltic.

Materials and methods The problem was addressed by exploring potential sediment transport from two sites located in the Gulf of Gdańsk at depths of about 20 m. A total of 29 combinations of hydrodynamic variables, representing the most extreme possible situations in the area, including eight theoretical uniform wind fields over the entire Baltic Sea from the W, NW, N, NE, E, SE, S, and SW sectors, the wind speed of 30 m s^{-1} , as well as 21 historical extreme storms, retrieved from the HIPOCAS project database, were used.

Results and discussion The bottom velocities resulting from waves and currents at the dumping sites considered were computed using wave models (WAM, SWAN) and the M3D hydrodynamic model (based on the POM model). To estimate the velocities critical for bedload transport, formulae developed by Soulsby (1997) and Sawamoto and Yamashita (Proc Coastal Sediments 87:415–423, 1987) were used. The volumetric bedload transport was computed based on Meyer-Peter and Müller (1948). The model simulations demonstrated that, for the storm conditions analyzed, the current velocity in the area of the two dumping sites would be so low that it would practically not affect the magnitude of the bottom sediment transport. Thus, the resultant volume of bedload transported would be equal to that generated by the wave action. For the heaviest historical storm, the maximum transport is about $3 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$.

Conclusions Under conditions of theoretical storms, the bottom orbital velocities would be higher and the resultant sediment transport would reach almost $7 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ for northerly winds. However, this value is still very low compared with the volume of sediment being dumped. The findings of this study may prove useful in designation of future dumping sites.

Keywords Bedload transport · Coastal hydrodynamics · Coastal zone · Gulf of Gdańsk · Landfills

1 Introduction

Modernizing sea harbors is associated with waterway and basin dredging and the resultant need to manage the dredged material. Storage of the excavated material for which there is no use is an issue of concern for the coastal zone management worldwide (e.g., Van Dolah et al. 1984). Selection of

appropriate locations for off-shore dumping has to involve considerations regarding the depth of the natural bottom, allowing for deposition of a considerable amount of the excavated material, as well as the relevant hydrodynamic parameters, i.e., wave action, currents, possible shipping difficulties, and feasibility of site management and monitoring. The environment-friendly approach calls for the re-use of the excavated material in shore-protection measures (e.g., artificial shore nourishment) rather than just leaving it in the sea (Staniszewska and Boniecka 2015). Thus, the dumping site selection should consider the potential dispersal of the material dumped.

Extended studies on sediment transport in the southern Baltic Sea were carried out in the Pomeranian Bay (Christiansen et al. 2002; Emeis et al. 2002; Kuhrts et al.

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2004), in the Gulf of Gdańsk (Ostrowski et al. 2010; Gic-Grusza and Dudkowska 2017), and along the Lithuanian coast (Pupienis and Jankowski 2006). Most of those studies involved application of circulation and wave models as well as sediment transport and bottom boundary layer ones. The first research mentioned above was based on measurements of sediment suspension in natural scale (SW Baltic Sea). Ostrowski et al. (2010) determined the offshore wave climate using the numerical prognostic wave model (The Third-Generation Wave Model <https://github.com/mywave/WAM>) (WAM) and then used the UNIBEST-LT numerical program to calculate net sand transport on the cross-shore profiles at eight selected coastal locations in the eastern part of the Gulf of Gdańsk. To estimate the sediment transport rate, Pupienis and Jankowski (2006) calculated the critical shear stress velocity based on the hydrodynamic data derived from the Princeton Ocean Model (homepage: <http://www.ccpo.odu.edu/POMWEB/>; user guide: <http://www.ccpo.odu.edu/POMWEB/UG.10-2002.pdf>) (POM) using the code of Blumberg and Mellor (1987). Recently, Gic-Grusza and Dudkowska (2017) determined wave-induced shear stress and resulting sediment transport in the Gulf of Gdańsk. It should, however, be emphasized that most of the knowledge on sediment movement in the area of interest is based on qualitative findings (Harff et al. 2017). Reliable in situ measurements of bottom velocity and sediment transport, especially in the storm conditions analyzed in this study, are particularly difficult and thus observed values of those parameters are very rare for the Gulf of Gdańsk basin.

Identification of areas with high and low shear stress at the bottom made it possible to designate sites amenable for dumping and those likely to be affected by re-suspension and sediment transport, but more detailed studies are required to define an optimal location of a dumping site.

According to the HELCOM (2015) database,¹ there are 14 dumping sites in the southern Baltic Sea; three of them are located in the Gulf of Gdańsk and Puck Bay, at depths of 30 and 55–60 m, respectively (Fig. 1). Potential additional locations could be placed closer to the shore, at shallower depths (18–22 m), on the slope of the Gulf of Gdańsk (Fig. 1). In this work, we considered the appropriateness of those locations in terms of their amenability to the transport of the dumped material induced by hydrodynamic conditions. To this end, we checked whether the most extreme hydrodynamic conditions possible would disperse the deposit dumped. Sediment transport in the areas of dumping can occur once critical values of individual grain movement speed and sheet flow movement have been exceeded. We asked whether the most extreme hydrodynamic conditions possible would induce the bottom orbital velocity to exceed the critical level. To answer this

question, we modeled the Gulf of Gdańsk hydrodynamics (wind-generated waves and currents) under an assumption of the most extreme weather conditions possible. It appears that sediment transport under such conditions is possible, but the magnitude of transport would be so low that the amount of lost (dispersed) material would be negligible. Since there is a lack of observational data on sediment transport in the Gulf of Gdańsk, our findings—based on the results of widely implemented and well-validated numerical models—provide the first insight into the dispersion pattern of the area of interest.

2 Materials and methods

2.1 Study area, bathymetry, and sedimentary environment

Two possible dumping sites were designated in the western part of the Gulf of Gdańsk (see Fig. 1). Sites 1 and 2 are located about 10 and 2–8 km off the shore, respectively, 5 km away from each other, and at depths of 18–22 m. Sites 1 and 2 cover 2.58 and 3.56 km², respectively. Coordinates of the sites' corners are given in Table 1. The dumping material volume assumed is about 6×10^6 m³; this amount would be expected to change the bathymetry of the sites considered by shallowing them by about 1 m.

The Baltic Sea bathymetry data provided by the Institut für Ostseeforschung in Warnemünde (IOW) (Seifert and Kayser 1995) were used as an input to the Wave Forecast Model WAM. The data were thoroughly examined and adapted to the wave model requirements. For wave modeling of the Gulf of Gdańsk, the bathymetric data provided by the Naval Hydrographic Office, digitalized by the Maritime Institute in Gdańsk, were used.

The 1:200000 Geological Map of the Baltic Sea Bottom (Mojski 1988–1995) shows the bottom of coastal areas in the vicinity of the potential dumping sites considered here to be covered mostly by fine- and medium-grained sands. As shown by research conducted by the Department of Marine Geology, Polish Geological Institute in Gdańsk (PIG-PIB 2012), also most of the approach channel to the port of Gdańsk, which is one of the biggest harbors in the area, is covered by sands, predominantly mostly fine-grained, moderately well, and well sorted. The median grain size D_{50} varies from 0.18 to 0.88 mm; the amount of sediment with $D_{50} < 0.2$ mm being equal to the amount of sands with $D_{50} > 0.2$ mm. In this study, we assumed the dumping site bottoms to be covered by sands of 0.2 mm grain diameter.

The bedload transport in the study area is not well recognized. Some estimations of the sediment transport rate were performed for the eastern part of the Gulf of Gdańsk (Kaczmarek et al. 2010; Ostrowski et al. 2010; Chechko et al. 2015). However, all of those studies were focused on the

¹ The database covers dumping site areas reported by the HELCOM Contracting Parties according to the HELCOM recommendations for the reporting period 2011–2015.

Fig. 1 Location of dumping sites in the Gulf of Gdańsk in the Polish sector of the southern Baltic Sea

processes taking place at water depths of up to 10–13 m. The occurrence of sediment transport at depths greater than 15 m is mentioned by Uścińowicz et al. (2014) as well as in some documents related to the commercial projects and unpublished materials.

2.2 Extreme wind regime in the area

Analysis of long-term data on wind, wave, and current characteristics in the area of study was conducted using a modeling system developed within the project HIPOCAS, carried out at the Institute of Oceanography, University of Gdańsk

(Cieślíkiewicz and Paplińska-Swerpel 2008). The most extreme hydrodynamic conditions possible were identified in two different ways.

In scenario 1, an “artificial” storm, wave, and current fields for the entire Baltic Sea were simulated using the WAM, Simulating Waves Nearshore (homepage: <http://swanmodel.sourceforge.net/>; user guide: <http://swanmodel.sourceforge.net/download/zip/swanuse.pdf>) (SWAN), and POM models. The model input consisted of eight wind fields, uniform over the entire Baltic Sea, from the W, NW, N, NE, E, SE, S, and SW sectors and the wind speed of 30 m s^{-1} . This extreme value of the wind was taken from Cieślíkiewicz et al. (2016) where it was estimated based on 138-year NOAA, the Twentieth Century Reanalysis (20CR) (Compo et al. 2011) dataset. The 20CR dataset provides the first estimates of wind direction and speed from 1871 to 2008 at six-hourly temporal and 2° spatial resolutions. The time series of wind speed at six points selected over the central area of the Baltic Sea were analyzed, and more detailed statistical analysis was performed for wind speed at point (56.1893° N , 18.7500° E). The maximum wind speed in the 138-year period considered was $U_{\max} = 30.5 \text{ m s}^{-1}$ at the WSW direction. Because of this, in modeling of wind wave field for assumed artificial uniform wind fields over the whole Baltic Sea, for all eight cardinal

Table 1 Geographic coordinates of the dumping sites’ corners

	Longitude	Latitude
Site 1	$18^\circ 40' 36'' \text{ E}$	$54^\circ 30' 51'' \text{ N}$
	$18^\circ 39' 42'' \text{ E}$	$54^\circ 30' 23'' \text{ N}$
	$18^\circ 41' 11'' \text{ E}$	$54^\circ 29' 43'' \text{ N}$
	$18^\circ 42' 03'' \text{ E}$	$54^\circ 30' 15'' \text{ N}$
Site 2	$18^\circ 45' 02'' \text{ E}$	$54^\circ 28' 31'' \text{ N}$
	$18^\circ 47' 56'' \text{ E}$	$54^\circ 28' 31'' \text{ N}$
	$18^\circ 45' 02'' \text{ E}$	$54^\circ 27' 55'' \text{ N}$
	$18^\circ 47' 56'' \text{ E}$	$54^\circ 27' 55'' \text{ N}$

and sub-cardinal directions of the wind (W, NW, N, NE, E, SE, S, SW), the wind speed at 10 m above the sea surface (U_{10}) of 30 m s^{-1} was applied.

In scenario 2, the 21 historical extreme storms (in the period 1958–2001, details in Cieřlikiewicz et al. 2017) were selected, based on wave-field characteristics over the Baltic Sea retrieved from the HIPOCAS database, at the grid point between the two dumping sites considered (see Fig. 2 for details). For both scenarios 1 and 2, the Gulf of Gdańsk wave fields were computed using the SWAN model, with the open boundary conditions derived from the HIPOCAS database. All the simulations were run in a stationary mode to reflect the peak of each storm.

Therefore, a total of 29 most extreme wind regimes of a potential to occur at the two dumping sites designated were considered.

2.3 Hydrodynamic conditions

The wind-driven circulation was determined based on the 3D time-dependent hydrodynamic model (<http://model.ocean.univ.gda.pl/indexeng.html>) (M3D) (Kowalewski 1997; Jędrasik et al. 2008), which was based on the POM (Blumberg and Mellor 1987). The POM model has been designed to describe ocean hydrodynamics, e.g., upwelling, eddy dynamics, and circulation in the coastal waters, estuaries, as well as whole basins ocean areas.

The 3D velocity fields, the sea surface height, the temperature and salinity were directly solved by the model equations. As the POM model, the M3D was based on the 3D Reynolds-averaged Navier-Stokes equations. It assumed incompressibility and Boussinesq approximation, so that density variations were

neglected, except where they were multiplied by gravity in the buoyancy force terms, and the vertical pressure gradient could be obtained from the hydrostatic relation. The eddy viscosity and diffusivity were calculated by the two equation k - kl (Mellor–Yamada level 2.5) turbulence scheme (Mellor and Yamada 1982).

The M3D model was adopted to Baltic conditions (Kowalewski 1997). Due to the open borders of the Gulf of Gdańsk basin, it was necessary to link the Gulf's hydrodynamics with that of the entire Baltic Sea. Thus, the M3D was applied to the Baltic Sea and to the Gulf of Gdańsk sub-area, in a form adjusted to the coastal zone conditions. The M3D model, for coastal zone, was developed by two-way dynamic downscaling, allowing to model interdependent fine- and large-scale processes (Jędrasik 2014). Coastal fine mesh of the Gulf of Gdańsk with a horizontal resolution grid of 1 Nm was embedded into a coarser Baltic model of 5 Nm resolution.

The vertical domain in the water column was assumed as 18 σ -layers with narrower layers near the surface and bottom. The thickness of the surface and bottom layer, at each node of the numerical grid, was assumed to be 0.5 and 2% water depth, respectively, while the thickness in the middle of the profile being 8.3%. A logarithmic boundary layer, using constant bottom roughness z_0 of 1 cm, was assumed.

An open boundary is located between the Skagerrak and the Kattegat along the parallel connecting Skagen and Göteborg, where the water exchange with the North Sea takes place. The boundary condition was based on one-hourly observations of sea-level fluctuations at the Göteborg station provided by the Swedish Meteorological and Hydrological Institute (SMHI). A radiation condition based on the

Fig. 2 Configuration of computational grids in the Gulf of Gdańsk used in SWAN and WAM models; parameters of 21 historical storms were adjusted for the grid point (in a circle) located between the two dumping sites

Somerfield's concept for vertically averaged and normal to the boundary plane velocities V , was applied (Hedley and Yau 1998):

$$V = \frac{C}{h} (\eta - \eta') \quad (1)$$

where $C = \sqrt{gh}$ is the long-wave velocity, g is the gravitational acceleration on Earth, h is depth, and η is a free-surface elevation defined as the mean of the surface elevation values for grid points on the open boundary calculated based on the continuity equation. η' denotes a free surface elevation observed in the vicinity of the open boundary. The approach applied resulted in the smallest reflection effects. The salinity of water entering the Baltic Sea via the open boundary was assumed based on monthly mean vertical distributions, as determined by measurements along vertical profiles taken during research cruises in the area of the Skagerrak-Kattegat border. The data were collected in the Baltic Environment Database (BED) of the Baltic Nest Institute (BNI). The water temperature of the inflowing water was assumed to be identical to that in the Kattegat (an assumption of a null gradient perpendicular to the boundary).

The boundary conditions at the free surface were time-dependent wind stress and heat fluxes. Atmospheric forcing was performed using the data from the Interdisciplinary Centre for Modeling at the University of Warsaw (ICM), Poland. The surface boundary conditions for heat fluxes were described by bulk formulae analogous to those used in POM and parameterized according to the energy exchange across the sea surface through short- (Krężel 1997) and long-wave radiations, as well as sensible and latent heat transfer (Jędrasik 1997, subsequently revised by Herman et al. 2011). The input of the energy flux component due to a slight surplus of net precipitation, almost balancing evaporation (127 mm year⁻¹ during the last century, about 20% of annual net precipitation) (Rutgersson et al. 2002), was omitted. Wind stress drag coefficients were parameterized according to Hellerman and Rosenstein (1983). Following calibration of the model at the 5 Nm grid, the wind stress drag coefficient was eventually assumed to be 2×10^{-3} . Mean monthly discharges into the Baltic Sea of 167 rivers were used at the coastal borders. The relevant data were taken from BED made available by BNI.

Since the Baltic Sea is a non-tidal sea, the hydrodynamic conditions in the Gulf of Gdańsk depend mostly on the atmospheric conditions (winds), the Gulf's bottom topography and inflow of Vistula river waters (see, e.g., Robakiewicz 2000). Annual estuary outflow of the Vistula River equals 1040 m³ s⁻¹, and an absolute point of flood discharge increases up to 9190 m³ s⁻¹ (see Fal et al. 1997).

Until the M3D model has become reliable, it had been submitted to basic procedures as calibration (Jędrasik et al.

2004), verification (Jędrasik 1997), and validation (Jędrasik 2005). Owing to the scarcity of reliable current measurements in the area of interest, the 5-Nm-resolution M3D model has been subject to comprehensive validation against long-term observations of the sea level, salinity, and temperature. The results, concerning the spatial and seasonal variability in shallow and deep coastal waters as well as in the open sea, were examined in relation to the observed values. For details, see Kowalewski (2002), Kannen et al. (2004), Jędrasik (2005), and Jędrasik et al. (2008). The modeled sea-surface temperature fields were also compared with those obtained from the appropriate satellite SST images, as documented in Jędrasik (2005) and Kowalewski et al. (2009).

The vertical distributions of currents $U(z)$, the bottom current evolution in time, and the bottom current field at the dumping sites were estimated for eight test wind conditions (artificial storms).

The wind-generated wave field was computed using the model WAM cycle 4 (WAMDI Group 1988) implemented within the framework of the project PROZA project (Cieślakiewicz et al. 2014) in the Baltic Sea with the SWAN series III (Booij et al. 1999) being applied to the Gulf of Gdańsk. The models were operating in nested grids: 5 Nm in the Baltic Sea (WAM), 200 m in the Gulf of Gdańsk (SWAN), and 50 m in the Puck Bay (SWAN). The simulations produced information on the significant wave height (H_s), direction of the wave approaching the shore, the mean wave period (T), and the horizontal root-mean-square bottom particle velocity (u_{rms}). The spatial extent of the computational grids is presented in Fig. 2.

Previous research performed in the area of interest indicated that the wave-induced currents are negligible (Gic-Grusza and Dudkowska 2017). This is due to the so-called sheltering effect, caused by Hel Peninsula (Różyński 2010). However, it does not change the fact that a more comprehensive approach to the subject requires taking into account both the wave-induced current velocities and the coupled wave-current model (as it has recently been done, for example, by Franz et al. 2017), which is planned for the authors' future research work.

The three-dimensional current fields together with trajectories of particle tracers spreading out of bottom boundary layer were modeled by Cieślakiewicz et al. (2017). They calculated fields of bottom velocities due to both currents and wind-wave motion. During northerly winds, causing in the Gulf of Gdańsk extreme waves and most significant wind-driven circulation, the wave-induced bottom velocities are greater than velocities due to currents. The current velocities in the bottom layer appeared to be smaller by an order of magnitude than the wave-induced bottom orbital velocities. Namely, during most severe northerly storms analyzed, current bottom velocities ranged about 0.1–0.15 m s⁻¹ in the region of two possible dumping sites. The root mean square of wave induced near-

seabed velocities (u_{rms}) reached the values of up to 0.5 m s^{-1} over site 1 and ranged between 0.5 and 0.8 m s^{-1} over site 2. During most severe northerly storms analyzed in Cieřlikiewicz et al. (2017), the maximum bottom current velocities of up to 0.3 m s^{-1} were computed by M3D along the Hel Peninsula on its northern (open sea) side. SWAN modeled the maximum wind wave bottom orbital velocity values u_{rms} of up to 1.4 m s^{-1} , in the narrow strip adjacent to the Vistula Sandbar along the Gulf's south-eastern coast.

2.4 Bedload transport

The bedload transport under extreme hydrodynamic conditions was estimated (Eq. (10)), based on data produced by hydrodynamic modeling. The following input data were used:

- The shear velocity (u_*) calculated based on vertical profile of velocity below the z -level of 15 m (from the M3D model, 1 Nm grid resolution) according to the law of the wall (Eq. (2)) to calculate the shear stress (τ_c) in the presence of currents (Eq. (3)),
- The average bottom orbital velocity u_{rms} (from the wind-generated wave model SWAN, 50 m grid resolution) to calculate the shear stress τ_w in the presence of waves (Eq. (4)),
- The mean wave period T (from the wind-generated wave model SWAN, 50 m grid resolution), to calculate the friction factor f_w (Eq. (5)),
- The median of grain size D_{50} and the sediment density ρ_s to calculate the critical shear stress for bedload transport τ_{cr} , estimated based on the Shields curve (Eq. (7)).

In addition, the critical velocities for bedload transport, the single grain movement u'_{cr} , and the sheet flow u''_{cr} were calculated based on the wave period and the friction factor (Eqs. (8) and (9)).

The logarithmic current velocity vertical profile above the seabed (Soulsby 1997) is given by:

$$U(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \quad (2)$$

where $\kappa = 0.4$ (von Karman's constant).

The bottom shear stress in the presence of currents (Soulsby 1997) is:

$$\tau_c = \rho u_*^2 \quad (3)$$

The bottom shear stress in the presence of waves (Soulsby 1997) is:

$$\tau_w = 0.5 \rho f_w u_{\text{rms}}^2 \quad (4)$$

The friction factor (Soulsby 1997) is:

$$\ln f_w = -5.977 + 5.213 r^{-0.19} \quad (5)$$

where $r = \frac{u_b T}{2\pi k_s}$; k_s is the roughness coefficient; and u_b is assumed as $\sqrt{2} u_{\text{rms}}$.

The bottom shear stress in the presence of waves and currents (Wu and Lin 2012) is calculated as

$$\tau_{\text{cw}} = (\tau_c^2 + \tau_w^2 + \tau_c \tau_w \cos \alpha)^{0.5} \quad (6)$$

where α is the angle between the near-bottom current direction and that of the orbital velocity.

The critical shear stress for bedload transport, estimated based on the Shields curve (Soulsby 1997) is:

$$\tau_{\text{cr}} = \{0.3 / (1 + 1.2 D^*) + 0.055 [1 - \exp(-0.02 D^*)]\} (\rho_s - \rho) g D_{50} \quad (7)$$

$$D^* = D_{50} \left[g \left(\frac{\rho_s}{\rho} - 1 \right) \nu^{-2} \right]^{1/3}$$

where $\rho_s = 2650 \text{ kg m}^{-3}$ and $\rho = 1004 \text{ kg m}^{-3}$ are densities of sediment and water, respectively; ν is the kinematic viscosity of the fluid.

This value additionally allows to obtain the critical velocity for bedload transport (Soulsby 1997):

$$u'_{\text{cr}} = \left(\frac{2\tau_{\text{cr}}}{\rho f_w} \right)^{0.5} \quad (8)$$

The parameter u'_{cr} represents the threshold bottom orbital velocity and shear velocity of sediment motion for the onset of single grain movement. The critical velocity of sheet flow is given by the empirical equation of Sawamoto and Yamashita (1987):

$$u''_{\text{cr}} = 6 \left[\left(\frac{\rho_s}{\rho} - 1 \right) g D_{50} \right]^{0.5} D_{50}^{-1/3} \delta^{1/3} \quad (9)$$

where $\delta = \nu^{0.5} T^{0.5} \pi^{-1}$.

The volumetric bedload transport (Meyer-Peter and Müller 1948) is the sediment volume transported in 1 s through unit width ($\text{m}^2 \text{ s}^{-1}$) (see also Dudkowska and Gic-Grusza 2017; Gic-Grusza and Dudkowska 2017).

$$Q = 3.97 \left((\tau_{\text{cw}} - \tau_{\text{cr}}) (g (\rho_s - \rho) D_{50})^{-1} \right)^{3/2} \left(\left(\frac{\rho_s}{\rho} - 1 \right) g D_{50}^3 \right)^{0.5} \quad (10)$$

3 Results

The wind-generated wave fields were computed with a set of nested WAM and SWAN models for all the 29 test cases. Simulations involving the wind speed of 30 m s^{-1} blowing from the eight cardinal directions (artificial storms) showed the largest wave parameters to occur for the northern-sector winds (N, NE, and NW). In these situations, the significant wave height, wave period, and bottom orbital velocity were in excess of 18 m, 15 s and 2.5 m s^{-1} , respectively. These were the maximum values in the Gulf of Gdańsk.

The exact values of wave parameters at dumping sites 1 and 2 are shown in Tables 2 and 3. The highest significant wave height (H_s), wave period (T), and bottom orbital velocity (u_b) occurred at the northern-sector (NE) winds: $H_s = 6.5 \text{ m}$ (site 1), 7.8 m (site 2); $T = 9.6 \text{ s}$ (site 1), 10.5 s (site 2); $u_b = 1.25 \text{ m s}^{-1}$ (site 1), and 1.53 m s^{-1} (site 2).

The lowest values of those parameters coincided with the southern-sector (SW) winds: $H_s = 2.2 \text{ m}$ (site 1), 2.5 m (site 2); $T = 4.2 \text{ s}$ (site 1), 4.5 s (site 2); and $u_b = 0.1 \text{ m s}^{-1}$ (site 1), 0.12 m s^{-1} (site 2).

Simulations involving the 21 historical storms showed, for the Gulf of Gdańsk (on the northern border of the Gulf) and the vicinity of dumping sites, the maximum significant wave height to be 8.5 and approximately 3 m, respectively; the maximum wave period to be 14 and about 6 s, respectively; and the maximum bottom orbital velocity to be 1.6 and about 0.5 m s^{-1} , respectively.

It can be concluded, based on the results of simulations for all the conditions analyzed, that the velocity due to wave action near the bottom, crucial for the sediment transport, is higher at dumping site 2 than at site 1, except for S and SE winds.

Three-dimensional time-invariant wind-induced current fields were calculated with the M3D model for each of the eight uniform wind test cases (artificial storms). Vertical profiles of current velocity at the two dumping sites for these test cases are shown in Fig. 3. For the strongest currents (generated by the SE, E, and S winds), the surface velocities reach 1–1.4 and 1.3–1.6 m s^{-1} at sites 1 and 2, respectively. The corresponding bottom current velocities are 0.15–0.17 and 0.2–0.24 m s^{-1} at sites 1 and 2, respectively. The velocities of surface currents generated by winds from the western and northern sectors (SW, W, NW, N, and NE) are 0.6–1 and 0.7–1.1 m s^{-1} at sites 1 and 2, respectively, whereas the velocities of bottom currents are 0.05–0.015 and 0.07–0.015 m s^{-1} at sites 1 and 2, respectively. The corresponding shear velocity, as calculated with Eq. (1), ranges within 0.001–0.01 m s^{-1} (Tables 2 and 3), the maximum shear velocity being generated by the south-easterly winds (SE, E, and S).

The friction factor (Eq. (5)) range is 0.01–0.02, based on the maximum bottom orbital velocity and wave period. The critical velocities for the onset of sediment movement u'_{cr} (Eq. (8)) and for the onset of the sheet flow u''_{cr} (Eq. (8)) estimated for the wave fields analyzed are $u'_{cr} \in (0.13, 0.22) \text{ m s}^{-1}$ and $u''_{cr} \in (0.5, 0.66) \text{ m s}^{-1}$.

Table 2 Values of parameters affecting bedload transport at site 1

Site 1	Data source	30 m s ⁻¹ wind							
		W	SW	S	SE	E	NE	N	NW
Wind direction (°)		0/360	45	90	135	180	225	270	315
H_s (m)	SWAN	2.4	2.2	2.8	4.1	5.1	6.5	6.3	3.2
T (s)	SWAN	4.4	4.2	4.9	6.3	7.6	9.5	9.6	5.4
u_b (m s ⁻¹)	SWAN	0.13	0.10	0.22	0.53	0.83	1.25	1.23	0.37
u_{rms} (m s ⁻¹)	SWAN	0.09	0.07	0.15	0.38	0.59	0.88	0.87	0.26
Wave direction (°)	SWAN	347	54	119	174	206	224	235	281
τ_w (N m ⁻²)	Eq. (3)	0.08	0.05	0.17	0.73	1.51	2.98	2.90	0.41
u_* (m s ⁻¹)	Eq. (1)	0.005	0.004	0.008	0.012	0.010	0.005	0.001	0.004
U_b (m s ⁻¹)	M3D	0.14	0.15	0.14	0.18	0.18	0.16	0.08	0.07
Bottom current direction (°)	M3D	215	219	150	114	79	31	24	203
τ_c (N m ⁻²)	Eq. (2)	0.03	0.02	0.07	0.15	0.10	0.03	0.00	0.01
τ_{cw} (N m ⁻²)	Eq. (5)	0.07	0.04	0.21	0.78	1.49	2.97	2.90	0.41
f_w	Eq. (4)	0.018	0.021	0.015	0.010	0.009	0.008	0.008	0.012
u'_{cr} (m s ⁻¹)	Eq. (7)	0.14	0.13	0.16	0.18	0.20	0.21	0.21	0.17
u''_{cr} (m s ⁻¹)	Eq. (8)	0.52	0.51	0.53	0.55	0.57	0.59	0.59	0.54
Q_v (m ² s ⁻¹) × 10 ⁻⁵	Eq. (9)	0.0	0.0	0.0	0.4	1.4	4.0	3.8	0.2

Results of calculations for eight test cases: uniform wind (30 m s^{-1}) over the entire Baltic Sea from cardinal directions

Table 3 Values of parameters affecting bedload transport at site 2

Site 2	Data source	30 m s ⁻¹ wind							
		W	SW	S	SE	E	NE	N	NW
Wind direction (°)		0/360	45	90	135	180	225	270	315
H_s (m)	SWAN	3.3	2.5	2.7	3.8	6.9	7.7	7.8	6.0
T (s)	SWAN	5.3	4.5	4.8	6.0	8.6	10.1	10.5	8.8
u_b (m s ⁻¹)	SWAN	0.35	0.12	0.17	0.44	1.18	1.48	1.53	1.07
u_{rms} (m s ⁻¹)	SWAN	0.24	0.08	0.12	0.31	0.84	1.05	1.08	0.76
Wave direction (°)	SWAN	329	39	112	169	218	228	234	256
τ_w (N m ⁻²)	Eq. (3)	0.37	0.07	0.12	0.55	2.80	4.04	4.23	2.32
u_* (m s ⁻¹)	Eq. (1)	0.003	0.001	0.011	0.013	0.012	0.002	0.004	0.005
U_b (m s ⁻¹)	M3D	0.10	0.04	0.20	0.23	0.22	0.12	0.09	0.06
Bottom current direction (°)	M3D	236	165	151	138	115	53	357	287
τ_c (N m ⁻²)	Eq. (2)	0.01	0.00	0.11	0.18	0.15	0.01	0.01	0.03
τ_{cw} (N m ⁻²)	Eq. (5)	0.37	0.07	0.19	0.65	2.79	4.04	4.23	2.33
f_w	Eq. (4)	0.012	0.019	0.016	0.011	0.008	0.007	0.007	0.008
u'_{cr} (m s ⁻¹)	Eq. (7)	0.17	0.14	0.15	0.18	0.21	0.22	0.22	0.21
u''_{cr} (m s ⁻¹)	Eq. (8)	0.53	0.52	0.52	0.55	0.58	0.59	0.60	0.58
Q_v (m ² s ⁻¹) × 10 ⁻⁵	Eq. (9)	0.14	0.00	0.01	0.28	3.55	6.19	6.64	2.66

Results of calculations for eight test cases: uniform wind (30 m s⁻¹) over the entire Baltic Sea from cardinal directions

The parameters affecting the bottom shear stress produced by wave-induced currents proved to be associated with the wave-driven average bottom orbital velocity (u_{rms}) and with the wind-driven current shear velocity (u_*). For all the eight test cases (artificial storms), u_{rms} is 1–2 orders of magnitude higher than u_* . It follows then that the bottom shear stress is mainly generated by waves, the wind-driven currents modifying it only slightly. The calculations performed (Tables 2 and 3) indicate that the wave-induced shear stress at sites 1 and 2 ranges within $\tau_w \in (0.05, 4.2)$ N m⁻². At the same time, the shear stress generated by wave-induced currents covers almost the same range, $\tau_{wc} \in (0.04, 4.2)$ N m⁻². The influence of wind-driven currents depends on the wind direction. The

weighted difference $(\tau_w - \tau_{wc}) / \tau_w$ is at its lowest for the northerly winds (N, NE, and NW), about $\pm 0.5\%$ at both sites. The difference is at its highest for the southerly wind (S): -23 and -63% at sites 1 and 2, respectively. However, the values of shear stress in such cases are low (about ten times lower than those for the northerlies); moreover, storms from the southern sector in the area are very rare.

Thus, based on the eight test cases with a uniform wind field, we showed that the impact of wind-induced currents on the bottom shear stress is insignificant (Fig. 3), and that it can be ignored in calculations of sediment transport. The results obtained concern the magnitude of transport induced by wave action. With this assumption, we computed the magnitude of

Fig. 3 Vertical profiles of current velocity at the dumping sites calculated by M3D model, forced by 30 m s⁻¹ wind from cardinal directions, uniform over the entire Baltic Sea (eight test cases)

Fig. 4 The volumetric bedload transport for the northern-sector 30 m s^{-1} wind (left) and for the historical storm of November 1988 (right)

sediment transport for all the 29 test cases. Under the most extreme wind conditions (artificial storms), a substantial bedload volumetric transport ($Q_v \sim 10^{-5} \text{ m}^2 \text{ s}^{-1}$) at sites 1 and 2 occurred at wind directions E, NE, N, and NW (Tables 1 and 2); for every wind direction, the transport is larger at site 2 than at site 1.

All the 21 historical storms considered showed similar characteristics on the northern border of the Gulf of Gdańsk, i.e., the maximum significant wave height $H_s \in (5.33, 8.53)$, and the prevalent wave direction being from northern sectors. In the case of the heaviest storm (November 1988), the sediment transport, $Q_v = 2.1 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ occurred at site 2, the transport at site 1 being ten times lower.

It was assessed within this study if the change in bottom topography, caused by dumping of dredged material in deposition sites 1 and 2, may alter the hydrodynamic regime during most severe storms. It appeared the change of water depth over the deposition sites of order of 1 m does not change the wind wave and current fields. The 3 m decrease of water depth, over deposition sites, which actually exceeds the possible reduction of water depth estimated based on expected total volume of dredged material, was also examined in terms of potential change of hydrodynamic conditions in the study

area. It was found that that 3 m water depth decrease might result in 10% change of significant wave height in the wave shadow area directly behind the deposition sites. The change in the volumetric bedload transport caused by this variation of hydrodynamic conditions is at most of order of $10^{-6} \text{ m}^2 \text{ s}^{-1}$ and thus may be neglected.

The spatial distribution of sediment transport in the case of the uniform 30 m s^{-1} northerly storm and in the case of the most extreme historical storm (November 1988) is shown in Fig. 4.

4 Discussion and conclusions

The decision-making process associated with the designation of marine dumping sites for locations for dredged material should involve, in addition to numerous environmental issues, two important depth-related aspects: the material should be deposited deep enough to prevent dispersion of the dumped material and shallow enough to allow it to be re-used. We presented the methodology which can aid in such decision-making. To designate the best site for dumping, wind-generated wave field and wind-induced current field under

the most extreme conditions possible should be considered. Subsequently, the near-bottom orbital velocities under wave and current action as well as critical velocities for the relevant environmental conditions should be calculated for the potential location. If the critical bedload transport velocity is exceeded, the volume of sediment transported should be computed based on the total shear stress. The result should be examined in light of the total volume of material to be dumped.

We used the M3D hydrodynamic model of the Baltic Sea and the Gulf of Gdańsk to calculate the velocity of wind-induced currents and the WAM model for the entire Baltic Sea with downscaling of SWAN at the Gulf of Gdańsk to determine near-bottom orbital velocity under wind-generated waves. For the two potential dumping grounds in the Gulf of Gdańsk, we showed the critical bottom orbital velocities for bedload transport and for sheet flow to be exceeded during extreme storms. For the most probable storms (wind from northern sectors: NW, N, and NE), the near-bottom orbital velocity value is crucial, whereas the impact of wind-induced currents can be ignored. Subsequently, we calculated the total bedload transport resulting from wave-induced and current-induced shear stress. During an extreme storm, the volumetric bedload transport is on the order of $10^{-5} \text{ m}^2 \text{ s}^{-1}$ at one of the sites considered. This value, although noticeable, is insignificant compared with the volume of the material dumped. Based on these results, we conclude that dumping sites in the western Gulf of Gdańsk might be located at depths of 15–20 m. However, a more accurate quantitative estimate of the sediment transport in the study area requires more comprehensive in situ measurements and will be the subject of further investigation.

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