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Waves, Currents and Seabed Level Change in the Port of Gdynia During Extreme Events

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ABSTRACT: The primary purpose of the paper is to identify port areas most exposed to extreme hydrodynamic conditions (waves, sea currents, seabed level change). The results of modelling using SWAN wave model, MIKE 3D model, and reanalysis and measurement data were used in paper. Swell may exceed 0.8 m for winds exceeding 15 m s-1 from the west and south. During extreme conditions, sea currents can reach 0.4 ms^{-1} in the outer part of the bay adjacent to the port. Port basins do not show changes in the thickness of the seabed for the given maximum values of bottom currents. The most extensive deposition of the seabed and shore sediments (up to 0.04 m) is found on the Gdynia-Oksywie beach adjacent to the port and the approach fairway at the offshore currents. The outer area of the main breakwater is the most exposed to erosive activity (-0.012 m).

1 INTRODUCTION

According to Polish law, seaports that perform an international logistics function are critical to the country's infrastructure. Understanding the characteristics of waves in port areas, particularly those related to extreme events, is crucial for ensuring maritime safety, cargo handling logistics and design assumptions necessary for strength calculations. The Port of Gdynia is part of the 6th Trans-European Transport Network Corridor and is an important element of the domestic import and export infrastructure. Although the Gdynia Port is an inland port and is protected by the Hel Peninsula, which limits the run-up and development of high waves, in the area of the Gulf of Gdańsk waves can exceed 3 m [3, 4, 7, 14]. The highest maximum waves (99th percentile) according to ERA5 re-analysis, produced by ECMWF (European Centre for Medium-Range Weather Forecasts) data from 1981-2021 in this area exceed 9.5 m. Similar values, i.e. 9-10 m, were obtained by Leppäranta [11] and Soomere [15] in the southeastern part of the Gulf of Gdansk. According to calculated statistics based on meteorological data from IMGW (Institute of Meteorology and Water Management) and ERA5 re-analysis the average duration of the storm is over 98 hours. The average height of a significant wave on an annual basis in the period 1981-2021 in the Gulf of Gdańsk is 0.7 m, in the stormy season (September-March) is 0.8 m, and in the stormless season (April-August) it is 0.5 m [6]. This characteristic is related to geographical conditions. The Gulf of Gdańsk is closed from the north by the Peninsula of Hel, from the south and west by land, while the eastern part remains open and adjoins the waters of the open sea. The Gulf of Gdańsk is dominated by winds from the west and west-north, and as a consequence , the waves generated by the wind are characterized by a similar distribution of the direction of wave propagation. Undoubtedly, an essential role in the formation of extreme hydrodynamic phenomena is played not only by the local and by regional climate, including the impact of NAO (North Atlantic oscillation), but also the morphology of the bottom and the shape of the coast, particularly in the vicinity of the port [13]. Previous studies of wave run-up in the Gdynia harbour area have relied on semi-empirical methods [20, 21] or simulations performed on low-resolution grids, often describing the conditions of the Gulf of Gdansk rather than the harbour itself [5]. The complexity of modelling in port areas is also due to the fact that precise tools and adequate input data are required for this purpose, the resolution of which corresponds to the resolution of the computational grid without the use of inter- and extrapolation tools [12], and the accuracy of the input data translates into the accuracy of the simulations. In this study, the SWAN (Simulating WAves Nearshore) model with a computational grid resolution of 5 m x 5 m was used, which gives high computational accuracy in all inner harbour basins. The high resolution of the computational domain allowed for the inclusion of all piers and wharves, including breakwaters, while the boundary conditions from the coarse model allowed for a more accurate simulation in which wave run-up is not constrained, as it could be in a model without feeding initial conditions from another model. Multi-point measurements of the depth of the harbor seabed allowed the construction of a bathymetric grid that considers medium and small seabed formations, which made it possible to perform simulations of seabed thickness change. Simulations results of the parameters of wind wave and swell, speed and direction of sea currents, as well as the change in seabed thickness, can contribute to improvements in the planning of dredging activities, new investments, and protection of the waterfront and its infrastructure. The ability to forecast the extreme values, including the 99th percentile and 100-yr value return, will allow to make more accurate calculations for estimating the strength of marine and quay structures.

2 METHODS

2.1 *Study area*

The study area is the port of Gdynia, located in the central part of the Gulf of Gdansk (Fig. 1a). The port is located in the major part of the city and covers 755.4 hectares, of which the land area is 508 hectares. The port's wharf is more than 17 km long, of which as many as 11 km are used for transshipment. For more straightforward navigation, the generally accepted nomenclature of port basin names was used to characterize the parameters described (Fig. 1b). The port of Gdynia consists of 11 basins, as well as an awanport and a main track that connects all the basins. The port on the east side is bounded by a breakwater with three culverts. Analyzing the distribution of anemometric conditions used measurement data from a station located in the southeastern part of the port, at the Ist. Presidental basin. At the same time, the eastern boundary of the domain (behind the breakwater) is the edge of the boundary conditions implemented from a lower resolution model and a spatially more extensive domain covering the southern Baltic Sea.

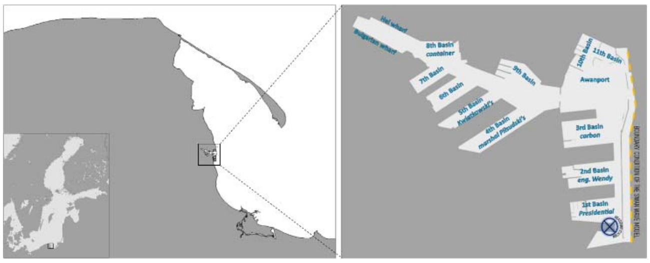

Figure 1. Study area: left – Baltic Sea (Gulf of Gdansk); right – Basins of the port in Gdynia

2.2 *Description the MIKE model*

MIKE 3D is a three-dimensional numerical model developed by the Danish Hydraulic Institute (DHI) for modelling many parameters of the aquatic environment. This paper focuses on modelling ocean currents. MIKE 3D is a tool that solves the momentum and continuity problem in three Cartesian directions. The model simulates ocean currents by taking into account the bathymetry of the bottom, density changes and external forces such as meteorological conditions (wind, atmospheric pressure) and other hydrographic conditions. To analyze the distribution of sea currents, detailed bathymetric data obtained from the Gdynia Port Authority was used, and an irregular triangulated grid was developed using this data with gradational grid density in areas of complex waterfront structures. The grid consists of approx. 6,000 elements (Fig. 2), and ten layers of σ are used for vertical description.

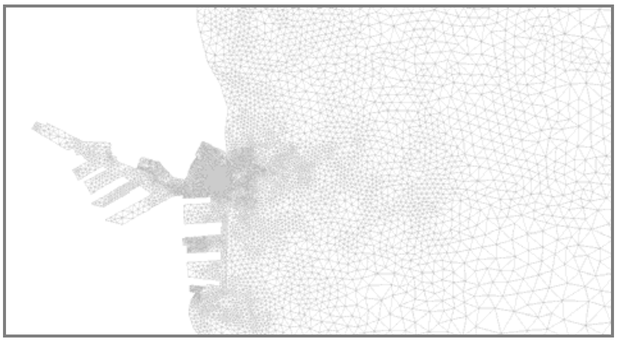

Figure 2. Triangular computational mesh with gradation resolution

2.3 *Description the SWAN model*

To analyze the spatial distribution of waves, the SWAN model was used, a third-generation model that calculates wind-generated wave parameters in deepwater and nearshore zones. The study used bathymetric data from the hydrographic work of the Gdynia Port Authority. The coastal conditions at the eastern boundary of the port domain are transmitted from a coarse model with a southern Baltic domain (Fig. 3a) and a resolution of about 1000 m. The developed computational domain of the port with a spatial resolution of 5 meters (Fig. 3b) allows for the inclusion of all piers and breakwaters, which are essential in the formation, extinction and refraction of waves. The boundary condition of the port domain is the eastern boundary of the domain, behind the breakwater (Fig. 3a). Both the coarse model, which is the source of the boundary conditions and the target model of Gdynia Harbor use a regular rectangular computational grid. The model uses the ST6 physics parameterization [16], and the coarse model was verified with multi-stream data sources in different depth zones.

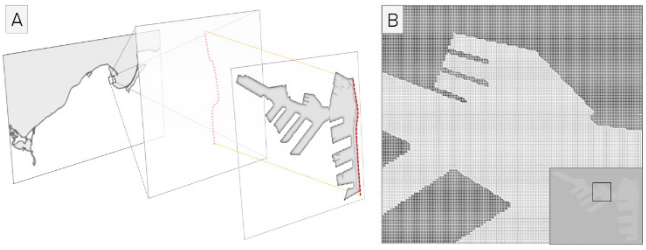

Figure 3. Computational regular rectangular grid with a resolution of 5 m (right: zoom)

2.4 *Observed and reanalyze data*

This paper uses anemometric measurement data from a station located near the 1st. Basin Presidental (Fig. 1) and reanalysis data [1] are the initial values to analyze and learn about the 99th Percentile and 100-yr return value in the Gdynia port area. The analysis uses measurement data from the last 15 years, i.e. 2006-2021, with a temporal resolution of 1h, and reanalysis data from 1976-2017 representing the historical background, and 2041-2100 is the prediction of the wave regime. The period 2041-2100 was chosen to identify changes in the furthest possible period available that may show less known conditions than the period before 2041. The reanalysis data are point data. Values from the point closest to the port of Gdynia (aprox. 2.70 Nm) were implemented into the coarse model as initial conditions to determine the change in wave conditions.

3 RESULTS

3.1 *Wind waves conditions*

To determine the wave conditions in the area of the port of Gdynia, anemometric data from the period 2006-2021 from the nearest station located at the basin of the 1st Presidential. . Based on them, the dominant wind direction (277° - winds blowing from the west account for as much as 31% of all wind directions) and the average (4.23 ms^{-1}) and maximum (19.6 ms^{-1}) wind speed were determined. Wave conditions were selected for these conditions. For the highest recorded speeds, i.e. exceeding 19 ms^{-1}, waves in the inner part of the port exceeded 0.55 m in significant wave height, especially in the area of the awanport and the main track. The determined average wind speed corresponds to wave conditions with significant wave height not exceeding 0.39 m. With the same wind conditions, the southern parts of the 1st-2nd and 4th-7th basins are characterized by smaller values of significant wave height than the inner part of the port, i.e. 0.375-0.38 m. The lowest values, i.e. 0.35 m of significant wave height, are characterized by the outer area of the port, directly behind the main breakwater, and this is the result of wave run-up attenuation in the 1st-3rd basins at the breakwater perpendicular to the direction of wave propagation (Fig. 4). The hatched area is the war port area and was excluded from further analysis.

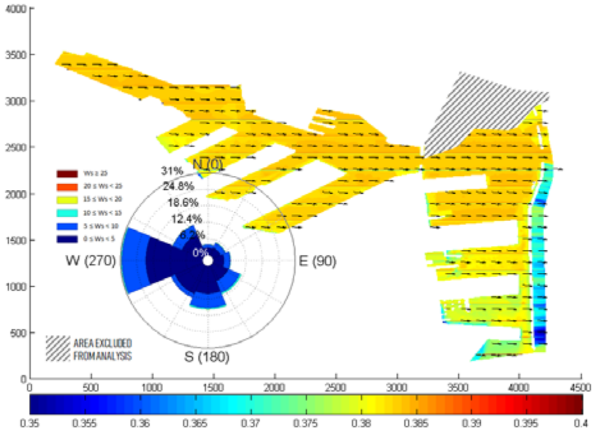

Figure 4. Significant wave height for mean wind speed (4.23 m s-1) and dominant wind direction (277°)

The values assimilated into the model are those from the reanalysis (Tab.1) and include the importance of the height of the significant wave, not the maximum, which is decidedly higher. The 99th percentile wave heights of the significant wind surge and the rosette (Fig. 5) are spatially close. The height of the significant wind wave from the dominant direction (277°) for the forecast value for the 2041-2100 period does not exceed 1.7 m in Basins 1st and 2nd, while in the other basins and the awanport it is in the range of 1.75-2.1 m. The highest values of the swell wave are characterized by the awanport and the track and adjacent parts of the 4th-9th basins, where the value reaches up to 0.26 m. The smallest values of significant wave height for both wind and swell waves are shown by the area behind the breakwater, where these values do not exceed 1.65 m and 0.21 m, respectively

Table 1. Forecasted and historical wave parameters for the analysis point located approx. 5 km from the Port of Gdynia

	period	99th percentile value	100-yr return value
Hs	1976-2017	2.2	3.8
	2041-2100	2.8	4.7
Tp	1976-2017	10.1	13.9
	2041-2100	10.9	14.8

The 100-yr return value is a crucial value for designers and engineers. It is particularly important in determining the boundary parameters of wave impact on hydraulic structures (Fig. 6). As with the 99th percentile, the value from the reanalysis was implemented into a coarse model and then fed into the boundary conditions of the port model. The values in the once-in-100-year event are significantly higher than the extreme 99th percentile. Wave height values of a significant wind wave from the prevailing westerly wind direction can reach up to 3.6 meters in height, while in the case of a swell, it can reach up to 1.2 meters. It should be taken into account that the values given as initiating conditions are forecast values derived from reanalysis. In addition, the model may not completely reflect actual conditions. Despite such limitations, it is possible to identify the port areas most vulnerable to above-average waves.

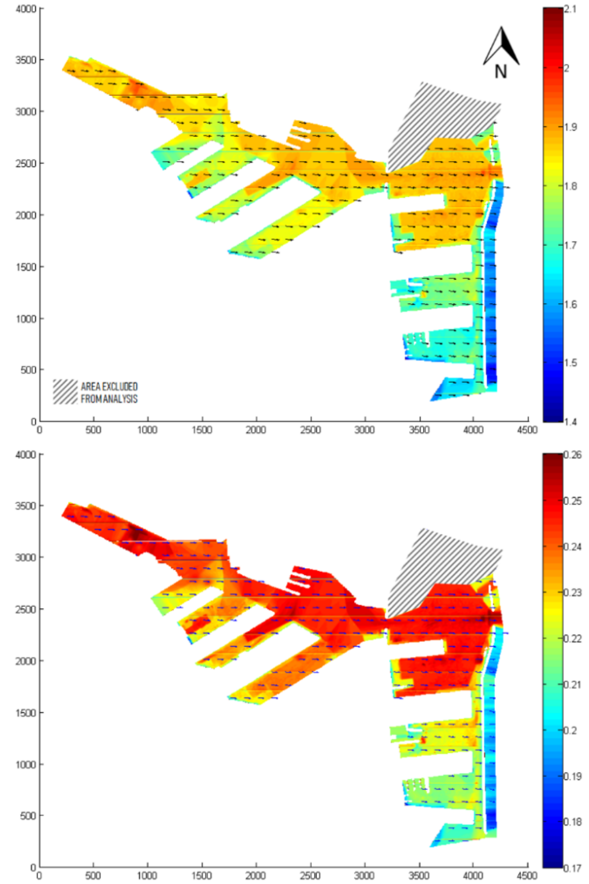

Figure 5. 99th percentile of significant wave height from the dominant direction: wind wave (left) and swell (right) projected for the period 2041-2100

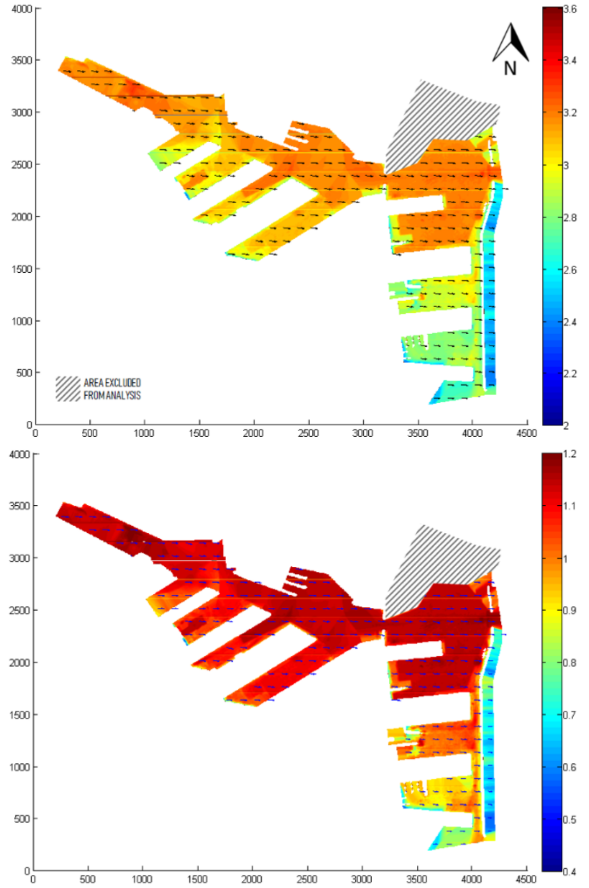

Figure 6. 100-yr return value of significant wave height from the dominant direction: wind wave (left) and swell (right) projected for the period 2041-2100

3.2 *Swell condtitions*

Swell, which are post-storm waves most often created when winds from one direction interact, can threaten moored vessels and ongoing unloading/loading. The height of the significant wave is an essential element that is crucial for shaping the swell conditions. Swell was determined for the highest projected significant wave heights (100-yr, 99th percentile). The highest swell values for both the 99th percentile (up to 0.26 m) and the 100-yr return value (up to 1.2 m) occurred in the 4th-7th basins, the awanport, and the main track (Figs. 5; 6). To identify the highest extreme values, point data were extracted from reanalysis [1], and 99th percentile and 100-yr return value values were extracted for the closest point of the port of Gdynia, and these values were implemented as initial conditions in a coarse model so that the results of this model could then feed as boundary conditions into the model in the port domain. Values were determined for both the historical period 1976-2017 and the prediction period 2041-2100, which makes it possible to trace potential changes in the wave regime and identify the most vulnerable areas. In addition, the paper analyzed simulations assuming four scenarios involving the highest speeds corresponding to the four main wind directions: N, S, W, and E (Fig. 7). Such analysis can be helpful in planning port and other ship maintenance/loading operations where the wind direction forecast is known, and a high wind speed warning has been issued. Variant (A) is the impact of the wind from the west (279°), where the highest measured speed is 19.6 ms^{-1}. The most exposed areas are the main harbor track and the awanport, where the waves exceed 0.6 m. The 1st-3rd basins and the southern parts of the 4th-9th basins, and the area behind the breakwater are characterized by low values of swell wave heights, i.e. 0.3-0.4 m (Fig. 7a). Variant (B) describes the spatial distribution of swell wave heights for winds from the north (12°) at a speed of 17.9 ms^{-1}. As with Variant (A), the 4th-9th and awanport are the most vulnerable to high waves, as these basins have relatively the longest unrestricted wave run-up. Variant (C) differs dramatically from the previous scenarios and presents a storm situation where the prevailing wind is an easterly wind (102°) with a speed of 15.1 ms^{-1}. Higher wave run-up heights in front of the breakwater on the Gulf of Gdansk side are evident, where high waves, i.e. 0.7 m, reach and break due to breakup by the breakwater, hence both higher waves 0.65-0.7 m and lower waves 0.0-0.2 m are observed at this location. In the 1st-2nd basins, the height of the breaking wave is in the range of 0.5-0.7 m, while in the rest of the port areas this value does not exceed 0.5 m (Fig. 7c). In scenario (D), where the wind was inflicted from a southerly direction (184°) with the highest recorded velocity from this sector of the direction - 15.5 ms^{-1} the highest waves of the swell formed in the areas with the largest unrestricted wave run-up, i.e. parallel to the breakwater on the side of the Gulf of Gdansk, the waves at this location exceeded 0.7 m. In other parts of the port, the swell was 0.3-0.6 m

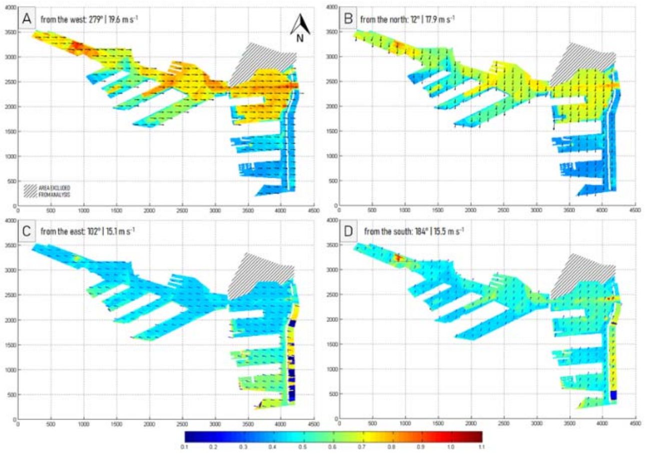

Figure 7. The height of the swell wave during highest wind speeds with corresponding wind directions: a) from the south; b) from the west; c) from the north; d) from the east

3.3 *Sea currents and seabed level change*

In the analysis of the distribution of surface sea currents generated, among other things, by the wind, two variants were calculated for the dominant directions of currents occurring in this part of the Gulf of Gdansk, i.e. from the south (longshore) and east (offshore) at a wind speed of 20 ms^{-1}. The selected speed is the maximum value recorded by the measuring stations located in the area of the port of Gdynia. In both cases, the velocities of surface currents reach up to about 0.40 ms^{-1} in the outer, adjacent to the port, part of the Gulf of Gdansk and, in the case of variant B, also in the awanport part (Fig. 8). Variant A (longshore currents) is characterized by a decrease in velocity and a multidirectional distribution of currents behind the main breakwater, which may be due to wind resistance and the extinction of their velocity. In the 1st-2nd basins, the currents are practically non-existent, the simulated value for both analyzed variants is in the range of 0.00-0.04 ms^{-1}. The 3rd basin and partially in the 4th-7th basins adjacent to the main runway, reach speeds not exceeding 0.12 ms^{-1} in variant A and 0.20 ms^{-1} in variant B. The main breakwater of the port of Gdynia is a barrier that properly protects the port basins from the effects of sea currents, only a part of the awanport, due to its proximity to the influent track, is exposed to stronger effects of higher speeds of sea currents.

In the analysis of the change in seafloor thickness, two dominant directions of bottom currents and the highest values of current velocity corresponding to these directions were selected (Fig. 9). The first case is that of bottom currents propagating from the south (local longshore currents), where the highest value of the currents' velocity is 0.79 ms^{-1}. The second scenario is that of currents propagating from the east (from the sea/gulf), where the highest velocity value is 0.53 ms^{-1} (Fig. 9). These values were set as initial values in the daily simulations.

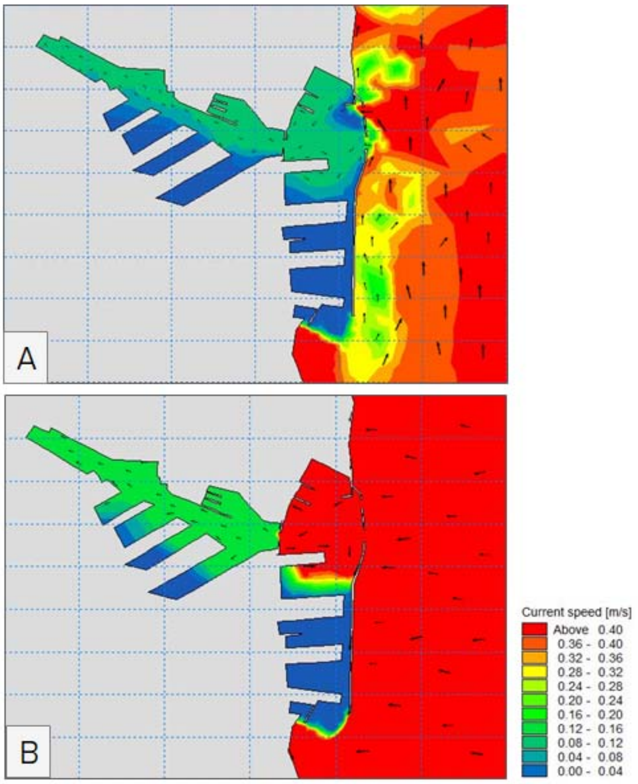

Figure 8. Spatial distribution of surface wind-driven sea currents with a speed of 20 m/s for the dominant directions, i.e. from the south (a) and from the east (b)

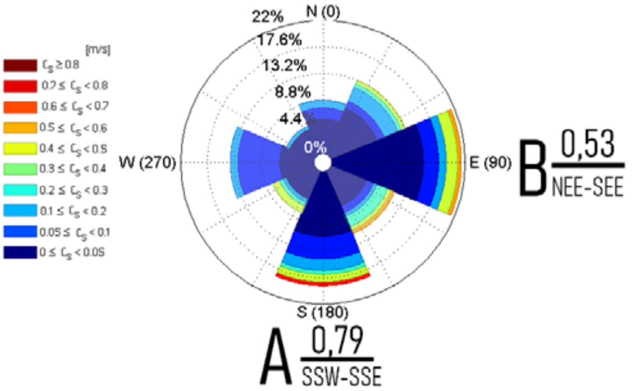

Figure 9. Maximum values of sea bottom currents velocities for dominant directions of current propagation: a) 0.79 m s-1 from south; b) 0.53 m s-1 from east

An important element in modelling changes in the thickness of the substrate is its geological structure (Fig. 10). Based on the lithological map of PIG-PIB [10], the type of substrate of the areas adjacent to the port was determined. Most of the substrate is sand, to a lesser extent sandy silt (Gdynia city beach adjacent to the southern part of the port) and sandy gravels (Gdynia-Oksywie beach). Also marginally present are muds and silts with admixture of gravel. The value of grain diameter was determined for each fraction, and so for gravel admixed with sand - 6.3 mm, sand admixed with gravel - 2.0 mm, medium sand - 0.63 mm and silty sand - 0.063 mm. The fraction of silt and silt admixed with gravel was not included in the analysis due to its borderline occurrence and insignificant share. Medium-grained sands were assumed as the substrate of the inner part of the port.

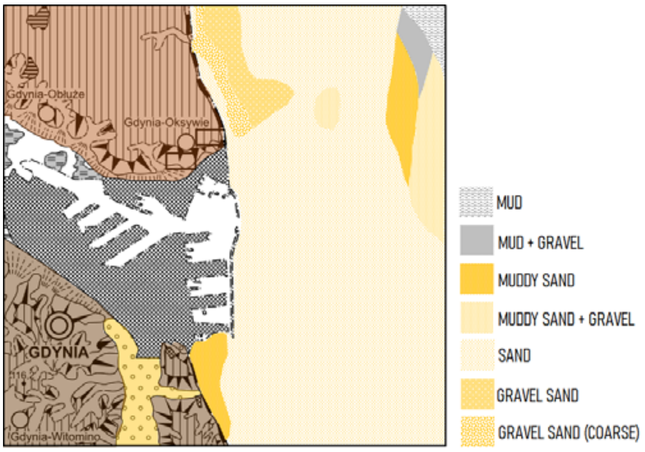

Figure 10. Lithology of the seabed near the port of Gdynia (based on PIG-PIB, 2005)

The coast, including the port of Gdynia and its vicinity shows a balance of shore erosion and accumulation (< 1 m/year) and locally dominant erosion (> 1 m/year) [18]. Although the bottom of the Gulf of Gdansk is characterized by a small variation in the thickness of bottom sediments, i.e. about 2 mm/year [17,19] local values of changes in the thickness of the substrate, after the impact of extreme velocities of bottom currents, indicate above-average erosion and deposition, especially in anthropogenically transformed areas. It should be emphasized that the results presented here concern extreme events that represent a minor contribution to the overall processes, which are compensated on a longer time scale. The obtained simulation results of both variants (Fig. 11), characterize ephemeral phenomena and correspond to ongoing studies of seabed sediment transport in the area of the Gulf of Gdansk [2, 8, 9]. The first variant (A), which is an analysis of the conditions for the change in the thickness of the seabed caused by longshore currents, does not show much change inside the harbour (0.0-0.25 cm). Accumulative character of sediment transport is characterized by the beach adjacent to Gdynia-Oksywie (northern part of the adjacent coast), where the change in the thickness of the bottom shows from 0.5 cm to 2.0 cm increment, and locally on the southern part of the coast adjacent to the port (city beach), where the increase in the thickness of sediments after 24 hours of influence of sea currents with a speed of 0.79 ms^{-1} is about 0.5 cm. The erosive area under strong longshore currents is the part of the seabed adjacent to the main breakwater and the part of the north coast behind the incline. Erosion in these areas reaches values of up to 1.2 cm of change in the thickness reduction of the seabed after the daily impact of the extreme values of the speed of the currents of variant A. Variant B is characterized by greater spatial variability and larger changes in seabed sediment thickness, despite the fact that the adopted speed of currents is lower compared to the value of Scenario A. The inner part of the port shows little or no change in seabed sediment thickness, i.e. 0.0-0.4 cm. Erosional changes of the seabed occur only on the marginal section of the northern coastline, adjacent to Gdynia-Oksywie. The farther part of the coast, closer to the port, shows a depositional character (about 3.0 cm of increment). The area of the approach track to the port, perpendicular to the coastline, is characterized by accumulative growth of bottom sediments, i.e. about 1.6 cm.

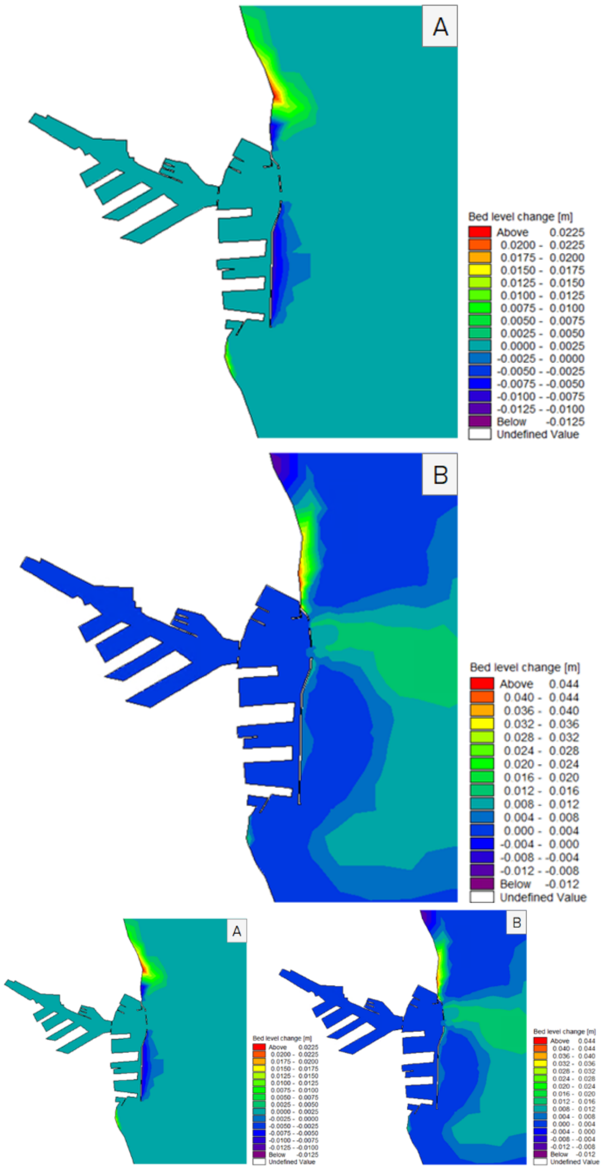

Figure 11. Change in thickness of seabed sediments according to conditions A – alongshore currents and B – from the open sea

4 SUMMARY AND DISCUSSION

High-resolution modelling with the use of appropriate tools can be an important tool in simulating hazardous hydrodynamic phenomena and their effects, which must be taken into account in future planning of port expansion, wharf protection, dredging works, the reception of bulky vessels into the port and the berthing and unloading of ships, as well as in adaptation measures. The paper shows that simulations calculated using the MIKE 3D model (sea currents, change in seabed thickness) and SWAN (wind and swell waves) are an important source of information in forecasting potential hazards. This paper presents the characterization of the wind surge in the Gdynia post area, including the prediction of extreme conditions. The forecasting of swell was carried out for four scenarios, which include the maximum values of wind speed measured at the station located in the southern part of the port as well as for the extreme values of significant wave height determined on the basis of reanalysis taking into account the prediction for the period 2041-2100. In addition, the paper includes an analysis of the spatial distribution of sea currents in the area of the port of Gdynia and the change in the thickness of the seabed caused by the extreme values of the speed of bottom currents. Both of these factors, directly affect the change in the shape of the seabed, and thus the conditions in the dredged waterways and the potential release of hazardous pollutants accumulated in port sediments. Knowing the detailed characteristics of wave and sea currents in each basin under extreme storm conditions allows preventive measures to be taken that can negate damage from inadequate ship mooring and coastal protection safeguards, as well as support the decision-making process for ship traffic in the port. Knowing the extreme values, especially the values in a once-in-100-year event can be crucial for strength calculations of shoreline structures and infrastructure. The most exposed part of the port, under extreme conditions, is the awanport (outport), where the speed of wind-generated currents (20 ms^{-1}) can reach 0.4 ms^{-1}. The largest change in the thickness of seabed sediments in the case of the scenario assuming daily impact of longshore currents with a speed of 0.79 ms^{-1} occurred in the area of the northern part of the coast adjacent to the port (Gdynia-Oksywie beach), where there was an increase in thickness from 0.5 cm to 2 cm, while the largest erosion transport occurred at the main breakwater. Currents from the eastern direction (transport from the sea) were characterized by sediment accumulation (+ 2.0-2.5 cm) in the vicinity of the port's approach track. It should be noted that the simulation assumed a daily impact of such strong currents, which in the actual distribution represent a small share and are ephemeral in nature, and the sedimentological environment of the seabed maintains the balance of erosion-accumulation balance on a longer time scale.

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