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Cieślikiewicz Witold

Dudkowska Aleksandra

Gic-Grusza Gabriela

Institute of Oceanography, University of Gdańsk, Gdańsk, Poland

Port of Gdańsk and Port of Gdynia's exposure to threats resulting from storm extremes

Keywords

critical infrastructure, Port of Gdynia, Port of Gdańsk, storm extremes, Gulf of Gdańsk hydrodynamics

Abstract

This study is intended to make a first estimate of the exposure of the two Polish largest ports – Gdańsk and Gdynia, localized in the Gulf of Gdańsk – to threats from storm extremes. These ports are elements of the Polish critical infrastructure and presented analysis is one of the tasks related to critical infrastructure protection. Hypothetical extreme meteorological conditions have been defined based on 138-year NOAA data and assumed wave fields for those conditions have been generated. Using HIPOCAS project database the 21 extreme historical storms over the period 1958–2001 were selected to simulate realistic conditions in the vicinity of the ports. The highest significant wave height was found to be nearly 4 m in the vicinity of Port of Gdańsk and nearly 2 m in the vicinity of Port of Gdynia. A future intensification of these wave conditions should be considered due to the climate change and sea level rise.

1. Introduction

According to the Polish Act of April 26th, 2007 on crisis management, sea ports, which are logistic centers of international nature, are part of the critical infrastructure of the country. Characteristics of threats to ports and the assessment of the risk of their occurrence is one of the elements of the critical infrastructure protection plans.

The Port of Gdańsk (*Figure 1*) is one of the biggest Baltic ports. The first port infrastructure was established in Gdańsk already in the early Middle Ages. Now the port plays a significant role as a key link in the Trans-European Transport Corridor No. 1 connecting the Nordic countries with Southern and Eastern Europe. The inner port is a part of the port of Gdańsk, including the area along the Dead Vistula and the Port Canal handles containerised cargo, passenger ferries and ro-ro vessels, passenger cars, and citrus fruit, sulphur, phosphorite, and other bulk.

The other quays fitted with versatile equipment and infrastructure are universal in use and enable the handling of conventional general as well as bulk cargo such as rolled steel products, oversize and heavy lifts, grain, artificial fertilizers, ore and coal.

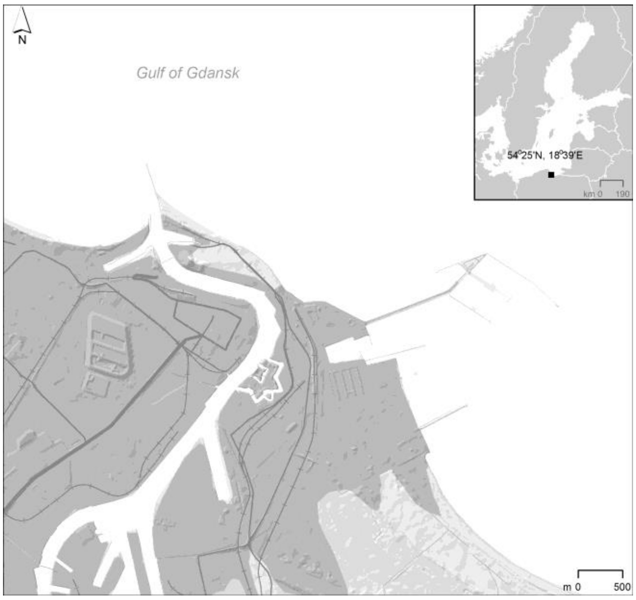

Figure 1. Port of Gdańsk

The deep water outer port, intended to handle energy raw materials such as liquid fuels, coal and liquefied gas, is situated immediately on the waters of the Gulf of Gdańsk, along the piers ranging 220 to 765 m in length. It can accommodate the largest vessels navigating the Baltic Sea. The fairway is 17 m deep. The area of port is 653 hectares of land and 412.56 hectares of water bodies[1]. Currently the outer port is being extended. A new deep-water container quay is under construction.

The Port of Gdynia (*Figure 2*), which was built in the twenties of the previous century, handles mainly general cargo, transported in containers and a ro-ro system, regular short sea shipping lines and ferry connections. The Port of Gdynia is an important link in the Corridor VI of the Trans-European Transport Network.

Figure 2. Port of Gdynia

There are two modern container terminals and bulk terminals located in the Western Port of the Port of Gdynia. The Port of Gdynia, which is protected by the Hel Peninsula, has very favourable navigation conditions. There is a 2.5 km long outer breakwater and a 150 m wide and 14 m deep entrance to the port. The quays at the Port of Gdynia are 17,700 meters long, of which over 11,000 are used for handling operations. The total area of the port is 755.4 hectares, including the land area of 508 hectares[2].

The analysis of threats to ports should be focused on the extreme conditions that can cause extraordinary damage to structures and coast. The port infrastructure is designed to withstand the highest wave-induced force over its lifetime. However, the selection of the design wave is usually quite a complex problem, especially when a joint probability distributions of wave heights and water level should be taken into account. According to [18] the designed wave is likely to be presented in terms of the significant wave height H_s. The probability of other heights occurring, in the relation to H_s, can be calculated using the Rayleigh probability distribution. Hence, in this work, we focus our analysis on the significant wave height.

In the Baltic Sea Region wind conditions are dominated by westerlies, with the average values 7–8 m/s. The highest wind speeds ever recorded in the open Baltic are greater than 30 m/s [12]. The southern Baltic Sea is dominated by winds from SW and W directions (westerly and south-westerly winds), throughout the year as well, with the exception of spring. Also, for high wind speeds the wind direction may differ from SW and W winds. Strong winds occur mostly in autumn and winter.

The Baltic Sea wave climate is mild. According to measurements and numerical simulations the typical long-term significant wave heights are about 0.6–1 m offshore and in the open parts of larger sub-basins, and 10–20% lower in the nearshore regions [19]. However, occasionally during severe storms, much higher waves occur. For example, the significant wave height of 7.7 m was recorded in the northern Baltic Proper on Dec 22, 2004. The maximum individual wave height in that record was equal to 14 m. Some estimations based on measured data showed the significant wave height of that order for the storm of Jan 13–14, 1984 at Almagrundet off the Swedish coast. There is also an evidence of H_s = 9.5 m observed offshore Saarema on Jan 9, 2005 (see [12], [17]).

In the area of the Gulf of Gdańsk generation and transformation of waves is limited by an open water fetch distance and complex bathymetry. A sheltering effect in the Gulf reduces wave energy compared to open coast areas and protects the Gulf from storms. In [15] the so called sheltering effect inside the Gulf of Gdańsk was discussed and estimated by the ratios of average monthly significant wave heights between two locations: deepwater open sea and the point deep within the Gulf. The relative reduction in wave height was found to be about 45% for the winter months and 33% in summer. According to the geographic configuration of the Gulf and the combined rise in storminess and evolution in extreme wave direction the sheltering effect of the Gulf can vary over the locations within the Gulf. Monthly mean significant wave height based on simulations and observations in the Gdańsk basin is in the range of 0.8–1.6 m [12]. Numerical simulations reported by [19] indicate that H_s during severe storms may

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[1] https://www.portgdansk.pl/en
[2] http://www.port.gdynia.pl/en/

even reach 9.5–10 m in the south-eastern part of Gulf of Gdańsk. Those values, even though may be somewhat overestimated are, however, of the order of recorded values referred to above [12], [17].

In the coastal zone of the Baltic the surface waves (wind waves and swell) have the most significant impact on the hydrodynamics, since the tide range in the Baltic is very small. There is a lack of long-term observational data allowing the determination of extreme H_s values near the ports of Gdańsk and Gdynia. There are some investigations reported that are based on semi-empirical methods, or carried out on coarse grids. An example of such an approach can be found in [23], [24], where the Krylov method [13] was utilised. However, the results obtained by applying the Krylov method and by using similar techniques are of limited value nowadays. The third generation wave forecasting models like WAM and SWAN are now preferred. The evolution of storminess characteristics over the Gulf of Gdańsk has been investigated by [15]. It was done by comparing the two sub-periods: 1958–1979 and 1980–2001. The growth in storminess in January and less vivid augmentation in February, October, November and December has been noted. Moreover, extreme waves from the western sector were found to be more frequent. The increase in the frequency and intensity of storms in the Baltic Sea is caused by the intensification of westerly winds at the relevant latitudes [23]. According to [8] projections of changes in wind climate in the Baltic Sea area are very uncertain. However, there is a slight tendency for an increase in the daily average wind speed on a seasonal basis.

In this paper the basic wave parameters i.e. the significant wave height and the mean period, and the orbital velocity at the sea bottom, appearing in the vicinity of the Gdańsk and Gdynia ports during the extreme weather conditions are estimated. For this purpose, two approaches are used.

1. The 21 extreme historical storms in the period 1958–2001 are selected and examined. The wind wave fields' characteristics over the Baltic Sea were taken from the 44-year hindcast generated within the framework of the project HIPOCAS [4], [5]. It was the first attempt to create a set of long-term wave data for the Baltic Sea, using the WAM model.
2. The maximum wind speed over the central area of the Baltic Sea was estimated based on the 138-year NOAA data [6]. For this extreme wind a number of "artificial" storm wave fields with a homogeneous distribution of wind velocity vectors over the entire Baltic Sea were simulated for W, NW, N, NE, E, SE, S, SW wind directions.

In order to assess the local extreme wind wave conditions in the vicinity of ports in greater detail the simulations in higher spatial resolution were performed. The regional model SWAN (Simulating Wave Nearshore, [9], [1]) driven by the output from the WAM model was used. This modelling tool is widely used around the world, for both the scientific purposes and for solving the problems related to the management of coastal zone.

Based on the long term data analysis, the maximum significant wave heights for the selected 21 extreme storms were estimated to be 3–3.9 m, with the median equal to 3.4 m, and 0.7–1.7 m with the median equal to 0.9 m, for the vicinities of the Gdańsk Port and the Gdynia Port, respectively. Such estimates of extreme wave heights indicate that the location of Gdańsk and Gdynia harbours may be considered advantageous with respect to exposure to storm wave, when comparing with other major harbours in the Baltic Sea.

On top of the analysis of significant wave height field, that may appear in the vicinities of the main harbours of the Gulf of Gdańsk during extreme storms, some estimations of the corresponding horizontal particle velocities near the sea bed are also given in the present paper. Those basic characteristics of bottom velocity may be important for estimation of sediment transport occurring during extreme storm conditions. This is particularly important for locations near the approach fairways of the ports and for the management of dredging activities.

2. Data and methods

The long-term wind wave parameters for the Baltic Sea region are derived from the 44-year hindcast wave database generated in the framework of the project HIPOCAS [4], [5]. This data set was produced using the WAM model [22]. Some other examples of WAM setup and validation for the Baltic Sea may be found in [2], [3], [14]. The wind wave filed hindcast utilized in this study was conducted over the period 1958–2001. The modelling area covers the whole Baltic Sea together with the Danish Straits. The spatial grid is regular in spherical rotated coordinate system similar to that used by GKSS in the REMO model, with resolution $5' \times 5'$ (about 5 Nm in the modelled area). In spectral space, the 25 frequencies ranging from 0.050545 Hz to 0.497855 Hz and corresponding to the wave periods from 2 s to 19.8 s were used, the directional resolution was equal to 15°.

The output from the model WAM running in the coarse resolution grid establishes the boundary conditions for the model SWAN operating in high-resolution grid covering the area of the Gulf of Gdańsk.

The SWAN numerical model [1], [9], allows the estimation of surface gravity wave parameters for a given seabed topography, wind field, sea state, and the current field.

Both WAM and SWAN determine the generation of waves by wind and wave propagation in time and space, taking into account a number of physical phenomena determining the wave field. These are mainly shoaling, refraction, nonlinear interaction between waves, and wave energy dissipation caused by whitecaping. The model SWAN, which is designed specifically for coastal zone and shallow sea areas, additionally includes energy dissipation by friction of the bottom and refraction due to ocean currents [2], [20].

SWAN model simulation was performed in this study on a grid with a spatial resolution of 200 m × 200 m, covering the entire Gulf of Gdańsk. Boundary conditions in the form of a monochromatic wave parameters are set on the Gulf of Gdańsk open border. This northern border of the computational grid of the SWAN model includes 11 WAM grid points, as shown in *Figure 3*.

All the SWAN simulations were performed in stationary mode, and the results are given for the peak of each storm.

2.1 Bathymetry input data

The bathymetry data for the Baltic Sea, used as input to the wave forecasting model WAM, were provided by the Institutfür Osteseeforschungin Warnemünde (IOW) [16]. These data were subjected to a very careful examination and then adapted to the wave model requirements.

For the modelling of waves in the Gulf of Gdańsk with SWAN high-resolution bathymetric data provided by the Naval Hydrographic Office in digital form prepared by the Maritime Institute in Gdańsk was used.

2.2 Meteorological input data

The meteorological forcing data, used within the HIPOCAS project, were 1-hourly gridded wind velocity fields provided by Forschungszentrum-Geesthacht (GKSS). The wind velocity hindcast covering the period 1958–2001 was performed in GKSS, with the atmospheric REMO model (REgional Model; [10], [21], [7]) forced with NCEP (National Centres for Environmental Prediction) reanalysis [11].

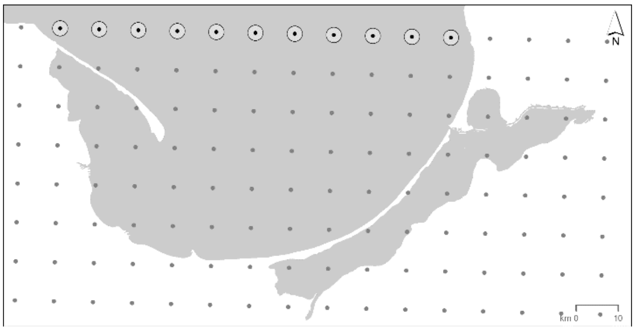

Figure 3. HIPOCAS grid points and boundary points (marked with circles) used in SWAN simulations (projection UTM 34N)

The REMO modelling area covers Europe and NE Atlantic with 0.5°×0.5° resolution. For the modelling of currents and waves over the Baltic Sea, a subset of gridded REMO data was extracted. The REMO data are given as 1-hourly time series over a rectangular grid in spherical coordinates. The spherical coordinates used by REMO model are the rotated geographical coordinate system with a pole at 170° Wand 32.5°N.

The maximum value of the wind speed over the central area of the Baltic Sea was estimated in this study based on 138-year NOAA, 20CR (the Twentieth Century Reanalysis [6]) dataset. The 20CR dataset provides the first estimates of wind direction and speed from 1871 to 2008 at 6-hourly temporal and 2° spatial resolutions.

In the present work the time series of wind speed at six points were analysed (see *Figure 4*). More detailed statistical analysis was performed for wind speed at point (56.1893°N, 18.7500°E) marked with circle in *Figure 4*. The maximum wind speed in the 138-year period considered was U_{max} = 30.5 m/s at the WSW direction. Because of this, in modelling of wind wave field for assumed artificial uniform wind fields over the whole Baltic Sea, for eight selected main directions of the wind (W, NW, N, NE, E, SE, S, SW), the wind speed U_{10} (wind speed at 10 m above the sea surface)of 30 m/s was applied.

It can be expected that the wind data, that are essentially based on numerical modelling with assimilated observations, do not reflect a realistic maximum values of wind speed fluctuations. However, since modelled meteorological data are used for the modelling of sea hydrodynamics, the adoption of wind speed of 30 m/s may be considered appropriate. It should be emphasized that wave field modelling for artificial homogeneous wind fields with different wind directions (W, NW, N, NE, E, SE, S, SW) is aimed to identify the main characteristic features of hydrodynamic conditions corresponding to different meteorological regimes.

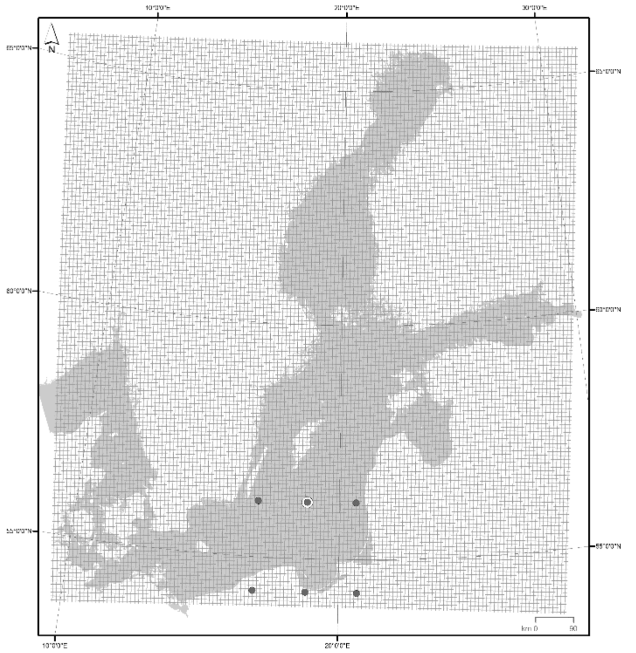

Figure 4. The location of points at which time series of wind were analysed(Projection UTM 34N)

Those conditions, obtained by numerical computations, do not reflect the real sea states and the assumed extreme value of wind speed may only generate the extreme storm conditions to some approximate accuracy. The present authors believe this approach allows for examining the principal features of extreme storm wave conditions in the studied sea area.

2.3 Selection of extreme storms

Based on the long-term analysis of the storm conditions and modelled significant wave height in the area of the ports of Gdańsk and Gdynia, the 21 extreme storms were selected. In addition, the extreme wind speeds that may occur in the central part of the Baltic Sea were determined and corresponding waves that may occur in the vicinity of the ports of Gdańsk and Gdynia were estimated. Parameters of time-varying wind wave fields generated using WAM model constitute a huge dataset, covering 44-year period 1958–2001. The following main wave parameters:

- significant wave height H_s
- mean period T_z
- peak period T_p
- main wave direction θ_0

for points within the area of Gulf of Gdańsk (see *Figure 5*) were extracted.

The automatic search for extreme storms was performed over the 44-year H_s time series for the central point of Gulf of Gdańsk with a threshold set to H_s = 2.8 m.

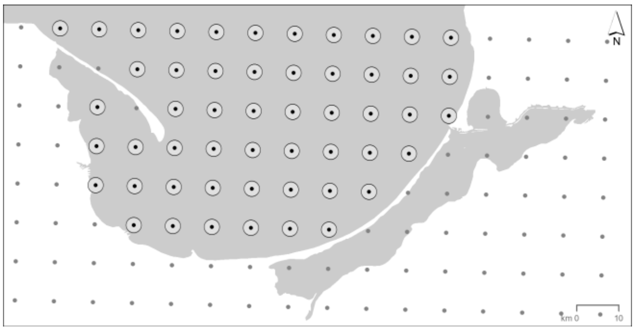

Figure 5. Locations of HIPOCAS project grid points used in this paper (marked with circles; projection UTM 34N)

Table 1. Storms dates and corresponding boundary conditions for the SWAN model simulations

Storm	Date	Time	H_s [m]	V [m/s]
1	1959.04.19	13.00	5.43	14.68
2	1961.12.21	08.00	6.29	13.33
3	1962.02.18	03.00	7.67	16.61
4	1962.02.21	04.00	7.52	15.18
5	1967.11.19	05.00	6.14	12.69
6	1975.11.21	11.00	6.94	14.52
7	1976.12.26	11.00	6.45	13.79
8	1983.01.20	02.00	7.30	15.09
9	1986.04.10	19.00	5.95	14.86
10	1988.11.29	23.00	8.53	16.09
11	1988.12.14	21.00	6.88	13.79
12	1989.10.01	00.00	6.30	13.49
13	1989.12.07	14.00	6.97	13.99
14	1992.02.17	11.00	8.29	17.17
15	1992.10.12	04.00	6.73	12.28
16	1992.11.08	15.00	6.85	14.95
17	1995.08.31	11.00	5.33	14.28
18	1997.04.11	23.00	8.10	16.82
19	1998.01.31	13.00	7.29	14.98
20	2000.01.21	06.00	7.57	15.51
21	2001.04.13	12.00	5.64	14.17

H_s – The maximum significant wave height on the northern border of Gulf of Gdansk [m]
V – Average wind speed used during SWAN simulations 200 m × 200 m [m/s]

Based on this procedure the mentioned above 21 extreme historical storms were selected. *Table 1* includes the dates of the storms as well as corresponding *Hs* on the northern border of Gulf of Gdańsk and the average wind speed. These parameters were used as boundary condition in SWAN simulations.

All the analysed extreme storms occurred during similar wind conditions, namely with similar wind speed of several meters per second from the northern direction. The maximum significant wave heights at the northern border of Gulf of Gdansk during these events were in the range of 5.33–8.53 m.

For all the selected storms the wind wave fields over the Gulf of Gdańsk were modelled with SWAN to obtain wave parameters in the vicinities of Gdańsk and Gdynia Ports. They are given below in Section 3.

In second approach, the additional modelling was carried out in order to identify the main features of the hydrodynamic conditions corresponding to different meteorological regimes. The eight cases of artificial homogeneous wind field with wind directions W, NW, N, NE, E, SE, S, SW were computed with the maximum wind speed of 30 m/s, which was determined based on the analysis of 138-year long dataset.

3. Results

As a result of described above simulations the information about the significant wave height, the direction of wave approaching the shore, the wave period, and the bottom velocity in the area of the port of Gdynia and Gdańsk was obtained. For all the considered 21 historical extreme storms the maximum significant wave heights H_s were found to be in the range of 3.0–3.9 m, in the vicinity of Port of Gdańsk, and in the range of 0.75–1.7 m in the vicinity of Port of Gdynia.

The wave periods *Tz* associated with the extreme significant wave heights were found to be in the range of 7.0–9.6 s, in the vicinity of Port of Gdańsk and in the range of 3.2–4.6 s in the vicinity of Port of Gdynia.

The maximum bottom velocities U_b associated with the extreme significant wave heights were found to be in the range of 0.8–1.1 m/s, in the vicinity of Port of Gdańsk and in the range of 0.1–0.3 m/s in the vicinity of Port of Gdynia. The details of extreme wave conditions are given in *Table 2*.

The spatial distribution of the resulting wave parameters for the peak of the most severe storm in terms of wind speed, i.e. storm No. 10, are presented in *Figure 6*. The maximum significant wave height reaches the value of 8.5 m at the northern border of Gulf of Gdańsk and approximately 1.7 m in the vicinity of the Port of Gdynia, and 3.9 m near the Port of Gdańsk. The associated wave periods are 3.8 s and 9.6 s in the vicinities of Port of Gdynia and Port of Gdańsk, respectively. The maximum bottom velocity reaches the value of 1.6 m/s in the Gulf of Gdańsk (Władysławowo region), 0.2 m/s in the vicinity of Port of Gdynia, and 1.1 m/s near the Port of Gdańsk.

Table 2. Values of maximum wave field parameters (H_s, T_z, U_b) during 21 historical extreme stores in the vicinity of ports of Gdańsk and Gdynia

	Gdańsk			Gdynia		
Storm	H_s	T_z	U_b	H_s	T_z	U_b
1	3.13	7.30	0.84	1.11	3.74	0.13
2	3.15	8.09	0.88	0.81	3.28	0.11
3	3.40	8.22	0.96	0.85	3.19	0.11
4	3.69	8.69	1.06	1.11	3.73	0.16
5	3.17	8.03	0.88	0.88	3.39	0.11
6	3.34	8.20	0.94	0.86	3.32	0.12
7	3.33	8.13	0.93	0.93	3.50	0.13
8	3.47	8.47	0.99	0.89	3.42	0.13
9	3.81	7.74	1.04	1.59	4.64	0.26
10	**3.93**	**9.62**	**1.12**	**1.67**	**3.81**	**0.18**
11	3.59	8.55	1.02	1.01	3.60	0.14
12	3.24	8.13	0.91	0.89	3.45	0.13
13	3.48	8.63	1.00	0.84	3.34	0.12
14	3.66	8.76	1.05	0.94	3.41	0.14
15	3.40	8.75	0.98	0.75	3.24	0.11
16	3.40	8.15	0.95	0.94	3.48	0.13
17	3.03	7.00	0.79	1.27	3.98	0.15
18	3.70	8.80	1.07	1.02	3.53	0.15
19	3.62	8.69	1.04	0.96	3.51	0.14
20	3.49	8.28	0.99	0.93	3.43	0.13
21	3.19	7.72	0.87	1.00	3.56	0.12

In the case of simulations carried out for an artificial storm with uniform wind speed of 30 m/s from various directions the greatest values of the wave parameters were obtained for the northern winds (N, NE, NW).

In these wind conditions the significant wave height exceeds 18 m, the mean wave period is about 16 s, and the velocity at the sea bottom assumes the level of 2.5 m/s. These are the maximum values found in the Gulf of Gdańsk. The spatial distributions of the discussed parameters are shown in *Figure 7*. Those values are unrealistic and clearly overestimated. That overestimation can be explained by the fact that in real storms it is very unlikely, if not impossible, for the wind speed to reach its maximum level along the whole critical fetch line and during a relatively long time period. One may expect that such an artificial and unlikely situation may lead to the very energetic wave field characterised by extremely high values of H_s.

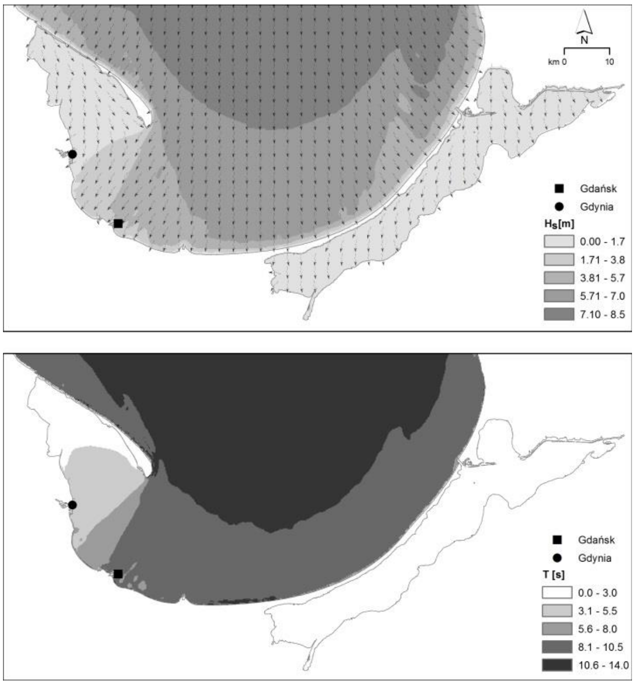

Figure 6. Results of wind wave modelling with SWAN for the peak of extreme storm No. 10: distributions of significant wave height H_s (upper plot) and the mean wave period T_z (lower plot)

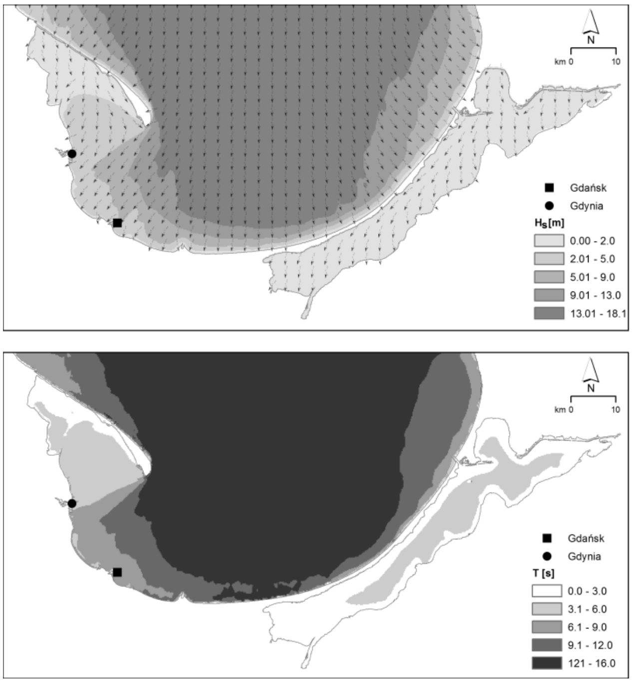

Figure 7. Results of wind wave modelling with SWAN for the artificial extreme storm with 30 m/s wind speed and the northerly wind direction (N): distributions of significant wave height H_s (upper plot) and the mean wave period T_z (lower plot)

4. Discussion

The degree of exposure to stormy wave action of the biggest Polish harbours located in the Gulf of Gdańsk has been investigated. This was done by examining extreme wave conditions in the vicinity areas of both Gdańsk Port and Gdynia Port. Extreme wave conditions have been simulated with SWAN model fed with boundary wave data modelled with the wave forecasting model WAM. The boundary wave data corresponding to extreme storm conditions were obtained by applying two approaches.

In the first approach, the wave boundary data for SWAN running over the Gulf of Gdańsk, were extracted from the WAM model simulations over the whole Baltic Sea, produced for the 21 selected severe historical storms that appeared to be extreme with respect to significant wave height computed for a grid point located in the central area of the Gulf. The WAM model simulations used in this first approach were taken from the 44-year long hindcast database produced within the EU project HIPOCAS.

In the second approach, the extreme wind wave fields over the Baltic Sea were obtained by applying the assumed wind speed equal to 30 m/s and for eight cardinal and intercardinal geographical directions (N, NE, etc.). The wind speed selected at the level of 30 m/s is close to the maximum wind speed found in the wind database of 138-year long NOAA reanalysis for a grid point located in the centre of the Baltic Sea.

The results of this work show that the maximum significant wave heights for the 21 selected extreme storms fall into the range of 3–3.9 m with the median equal to 3.4 m for the vicinity of Port of Gdańsk. For the vicinity of Port of Gdynia, the corresponding range is 0.7–1.7 m with the median equal to 0.9 m. Those estimates clearly demonstrate that the location of Gdańsk Port and Gdynia Port are favourable against other major ports in the Baltic Sea when the exposure to stormy wave action is concerned. The values obtained show this feature is of course much more pronounced for the Port of Gdynia.

There is a serious lack of continuous long-term wave climate data records for the Gulf of Gdańsk region. This paper fills this gap, to a certain degree, by providing at least some insight into long-term wave characteristics over the Gulf of Gdańsk and at points near its major harbours, which is based on numerically simulated values for real historical storms.

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