POAC'23
Glasgow, United Kingdom

Proceedings of the 27th International Conference on
Port and Ocean Engineering under Arctic Conditions
12-16 June 2023, Glasgow, United Kingdom

Ice dynamics on the Vistula Lagoon after the construction of a new navigable channel to the port of Elbląg

Tomasz Kolerski[1], Aleksandra Rzeźnik[1] Parisa Radan[1]
[1] Gdańsk University of Technology, Faculty of Civil and Environmental Engineering, Narutowicza 11/12, 80-233, Gdańsk Poland

ABSTRACT

From September 2022, the connection of the seaport of Elbląg with the Baltic Sea has taken place through a newly opened shipping channel with a sluice on the Vistula Spit. The creation of a deepened fairway through the Vistula Lagoon from the sluice to the port of Elbląg creates conditions for navigation. The implementation of this project arose from the need to open the port in Elbląg for a maritime transport, which will only occur in Polish territorial waters. Thus, it will not be necessary to enter the Vistula Lagoon through the Strait of Baltiysk, located in the Kaliningrad Oblast, which leads to the port of Elbląg function independently from the agreements between Poland and the Russian Federation. The 12 m/s wind speed was considered for different wind directions, which were obtained from three stations from 2014-2022. The mathematical model for the ice dynamic was performed by the DynaRICE model. The results showed for the north eastern and south western winds the water levels increases and decreases in Elbląg (Polish port) and at the mouth of Pregel (Russian) river. The maximum and minimum water levels for the Elbląg estuary were 0.3 and -1 m and those of Pregel estuary were around -0.3 and 0.3 m. It also was observed that the north eastern winds are more influential in ice jamming point of view, on the newly constructed structure. The maximum ice thicknesses for the north eastern and south western winds were 0.9 and 0.8 m, sequentially.

KEY WORDS: Vistula Lagoon; Port of Elbląg; Cut-off Chanel.

INTRODUCTION

On September 17th, 2022, at the 80th anniversary of the USSR's invasion of Poland, the new canal that allows vessels to sail from the Baltic Sea to its Elbląg port without passing through Russian territorial waters was opened. Elbląg the city on the shore of the Vistula Lagoon, in northern Poland, is separated from the Baltic Sea by a thin strip of land called Vistula Split. Until now, the only way across was through an opening near the town of Baltiysk into Russia's Kaliningrad Bay and required authorization from Russian authorities.

The freshly dug canal runs across Polish territory, around five kilometers (three miles) west of the town of Krynica Morska. The canal is currently accessible only to small boats due to its limited depth. Dredging works are ongoing and are due to end in September 2023, when the canal is due to be large enough to accommodate vessels up to 100 meters long and 20 meters wide, according to Polish authorities. Ecologists have criticized it, arguing that the canal will alter salinity levels in the Vistula Lagoon, endangering local fauna and flora.

The investment leads to changes in the area of the Vistula Lagoon through the construction of new hydrotechnical facilities, such as a sluice outer port or an artificial island for sediment separation. The Vistula Lagoon is a shallow water reservoir with a salinity similar to that of the Baltic Sea (Chubarenko, 2008). Administratively, the lagoon is a cross-border area, divided between the Republic of Poland and the Russian Federation. The hydrodynamics of the lagoon in the north-eastern part, belonging to Russia, is mainly regulated by water exchange through the Baltiysk strait. In the south-western part, which belongs to Poland, water movement is mainly caused by wind stresses (Chubarenko and Zakirov, 2021). In the winter season, practically every year, an ice cover appears on the lagoon. This is despite the observed climate changes leading to an increase in the average air temperature in this region by about 2 degrees Celsius over the last 70 years.

Many mathematical models of the Vistula Lagoon have been developed over the last decades, including two-dimensional (2D) hydrodynamic models (Szymkiewicz, 1992), 2D models composed of hydrodynamics, water quality and eutrophication modules (Chubarenko and Tchepikova, 2001; Kwiatkowski et al., 1997), and recently developed three-dimensional models used for waves, sediment transport and migration (Chubarenko et al., 2012; Kruk et al., 2011). Modeling of ice processes has been conducted by using two dimensional ice dynamic model DynaRICE (Kolerski et al., 2019), however the detailed geometry of the newly constructed structures were not included in the study.

In the current study, the ice phenomena are investigated by applying the DynaRICE two-dimensional river ice dynamic model (Shen, 2010). The model was developed to simulate river ice processes including ice formation and breakup, ice jam dynamics and ice load determination. Even though the model was primarily developed to reproduce ice dynamics in rivers, where the ice movement is mainly driven by water hydrodynamics, it has been successfully applied to a coastal lake subjected to sea tides (Kolerski et al., 2013).

The article uses the DynaRICE mathematical model to analyze the dynamics of ice in the Polish part of the Vistula Lagoon and its impact on the constructed engineering structures - the island and the inner port on the Vistula Spit. The model was calibrated based on data from satellite images, observations of water levels and ice thickness from February 2011 (Kolerski et al., 2019). It was assumed that the ice dynamics is a result of water exchange in the Baltiysk strait by changing the water level at the Baltic Sea and also as a result of the wind action blowing from variable direction. Attention was drawn to the changes caused by the existence of new structures to ice processes, including the formation of ice ridges and polynyas. The results showed that the ice thrust is most pronounced with northeasterly winds pushing the ice towards the southeast direction. The existence of a significant narrowing of the lagoon as the result of an artificial island leads to the concentration of ice in this area and its increase in thickness.

SITE DESCRIPTION

The sketch map of the Vistula Lagoon together with the location of the city of Elbląg and tributaries is presented in Figure 1. It is estimated that the Lagoon was created by cutting off the Baltic Sea with a strip of land about 5,000 years ago. Despite this, in the past, it periodically had connection with the sea through the Krynica Strait (before 1300 to 1510), the Elbląg Deep near Skowronki (in the years 1426-1431) and the strait near the town of Piaski (until 1455). Currently, it is connected to the sea by the Strait of Baltiysk (also known as Pilawska), which was created artificially in 1497. This transition contributes to the unique hydrodynamics of the lagoon. Due to the constant movement of water level in the sea and the lagoon, the highest flow velocities are achieved in the vicinity of the Strait in Baltiysk. It has a variable width from 400 to 860 meters and a depth of between 8 and 12 meters (Bielecka et al., 2003). As you move westward, the velocity decreases, reaching values close to zero in the lagoon area. The tributaries to the Lagoon on the Russian side are Pregel, Prochladnaja, Mamonowka, and Primorskaja, while on the Polish side there are Pasłęka, Bauda, Narusa, Stradanka, Elbląg, Nogat, Tuga, Szkarpawa and Wisła Królewiecka. The largest of these rivers is Pregel, which provides 62% of freshwater to the Lagoon (Chubarenko and Chubarenko, 1997).

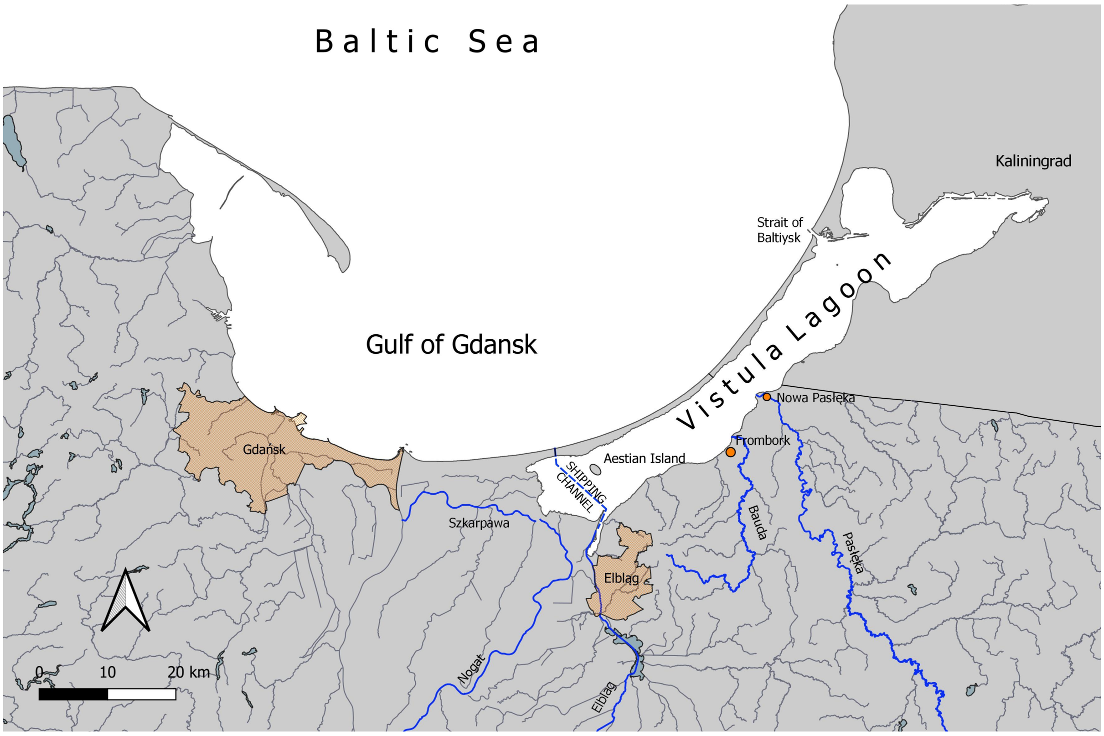

Figure 1. The area covered by the analyses; the shipping channel, the CDF area (Aestian Island) and the tributaries of the lagoon from the territory of Poland are marked

In the northern part of Poland, the weather and climate are significantly affected by the presence of the Baltic Sea, which leads to the formation of local, mesoscale and submesoscale air circulation. The phenomena that distinguish coastal regions from other parts of the country are breezes, coastal winds or squalls. For the Vistula Lagoon, apart from the location in the coastal zone, the Elbląg Upland has a significant impact on shaping local conditions. Steep slopes located on the side of the lagoon intensify the wind along the shore by directing it parallel to the shore, at the same time increasing its gustiness.

The local climate of the lagoon is affected by its location in the temperate zone, characterized by the clash of tropical and polar air masses, and the mixing of wet air masses from the west and dry air masses from the east. All this leads to the formation of seasonal variability of atmospheric conditions and affects wind speeds and directions. Strong and gusty winds are recorded especially in winter. They lead to the setting up of the water surface and the creation of a wave with a height of more than 1 meter and a length of less than 30 m. These waves are not very long but steep.

MATHEMATICAL MODEL

The mathematical simulation of the effect of wind in Vistula Lagoon was performed by DyanRICE model (Shen, 2010). This is a 2D coupled dynamics-hydrodynamics model, which simultaneously solves the hydrodynamics and ice dynamics equations, and exchanges information in coupling time steps. The model of water hydrodynamics is based on shallow water equations including ice effects (Liu et al., 1998). Ice condition comprises thickness and ice to water resistance with respect to the water and ice relative velocity. Seepage flow ice rubble is also handled by the model. Ice dynamics is formulated based on the force balance on ice acceleration. Newton's second law of dynamic force implemented on ice comprises wind, water, gravity, and internal ice forces (Shen et al., 2000). A table is provided with the descripted modelling parameters including model dimension and physical ice properties.

Table 1. Modelling parameters.

Parameters	Value	Unit
Manning's roughness coefficient for single ice layer	0.02	[-]
Manning's roughness coefficient for ice jam	0.06	[-]
Initial thickness of ice	0.2	[m]
Internal friction angle	46	[°]
Maximum concentration for the ice	0.6	[-]
Ice stoppage criteria	0	[-]
Wind stress on ice coefficient	0.0015	[-]
Average length of the lagoon (from SW to NE direction)	74	km
Average width of the lagoon (from NW to SE direction)	8.5	km
Initial Water level at the sea	0	m
Wind velocity magnitude	12	m/s
Water discharge at the tributaries (Polish side)	20	m^3/s
Water discharge at the tributaries (Russian side)	50	m^3/s

SHIPPING CHANNEL

The navigation channel connecting the port of Elbląg with the Baltic Sea provides a waterway leading through the lagoon. The total length of the channel will be 22,880 km - including crossing the Vistula Lagoon (10.176 km) and the Elbląg River (10.381 km). The waterway will be deepened to 5 m to ensure the entry of vessels up to 100 meters long and up to 20 meters wide into the port of Elbląg. For creating safe conditions for ships the breakwaters are located before entering the shipping channel from the Baltic Sea. They consist of two parts: the eastern breakwater in the form of an arch, which is projected into the sea and directed to the west, and the western breakwater, which is a simple structure projecting towards the north.

The sluice is the most important element of the Navigation Channel, located in the part connecting the Vistula Lagoon with the Gulf of Gdańsk. It aims to reduce the tides between the waters and at the same time allow the passage of ships. The double gates located in the northern and southern parts of the lock will move from west to east, closing the road or allowing ships to pass through. On the southern side an additional set of breakwaters were constructed inside the Lagoon to protect a quay.

Due to the rich biodiversity and ecosystem services of the Vistula Lagoon, which could be endangered by existence of the new waterway, the project includes the construction of an artificial island as ecological compensation. The island aims to create favorable conditions for ichthyofauna and ornithofauna, to mitigate the impacts of the development.

The island is to be located in the central part of the Lagoon, 2.5 km from the shore of the spit and is created to be from silt obtained during dredging as the Confined Disposal Facility (CDF). It is to have an area of 181 ha and a volume of 9.2 million m^3. It is expected that the shores of the island will be covered with reed rushes, while the central part will be meadows. This is to enable settlement by water and marsh birds, which are also the subject of protection of the area.

WIND CONDITIONS

The hydrological situation of the region is significantly affected by winds, which can lead to dangerous hydrological phenomena (storm floods, the influence of salt water in the mouths of rivers). This danger may be intensified by the facilities constructed as part of the Navigation Channel investment, hence an analysis of the frequency of wind speed and direction in the area of the Vistula Lagoon was carried out to develop the calculation scenarios. To analyze the situation, data on wind directions were obtained for three meteorological stations located in Elbląg, Frombork and Nowa Pasłęka. Each of the measurements covers the period from 2014 to 2020 (Figure 2). In the case of wind analysis, data from recent years were used to take into account current trends resulting from the observed climate changes. The source of the data is the Institute of Meteorology and Water Management - National Research Institute (IMWM-NRI).

For the Elbląg station in the 7-year measurement period, a range of wind speeds from 0.5 m/s to 22.3 m/s was observed. There is no tendency for the smallest measurements. A speed of 0.5 m/s is observed in all measurement years throughout the year. In the case of the strongest winds, i.e. the range of 12-22.3 m/s, it can be seen that it occurred only in the autumn and winter. During this period, the strongest storms occur over the Baltic Sea. It should be noted, however, that the wind directions in this case were different and the strongest recorded measurement blew from west to east. It is worth noting that the Elbląg station is located about 20 km from the shore of the Vistula Lagoon and the wind speeds recorded here are evidently lower than those blowing directly over the Lagoon.

For the Frombork station, the wind speeds ranged from 0.1 to 20.1 m/s. Values below 1 m/s were observed every month during the 7-year measurement period. The occurrence of lower wind speeds does not show any tendency. In the case of winds with a higher average speed, it can be seen that the measurements were more precise, registering even the slightest change in direction. The wind in the Frombork station area is also characterized by high variability of direction. The highest wind value during measurements was recorded in 2020, and the wind was from the east.

For the Nowa Pasłęka station, the wind speed during the 7-year measurement ranged from 0.1

to 54.7 m/s. Indicates that the highest measured wind of all three occurred for the above station, which was made in January 2018. The direction of the wind was from the northeast. This month there was an exceptionally strong wind that lasted for a week. The speed between 40-54.7 m/s occurred at the turn of 2017-2018. Such a strong wind has not reappeared during the 7-year record of measurements.

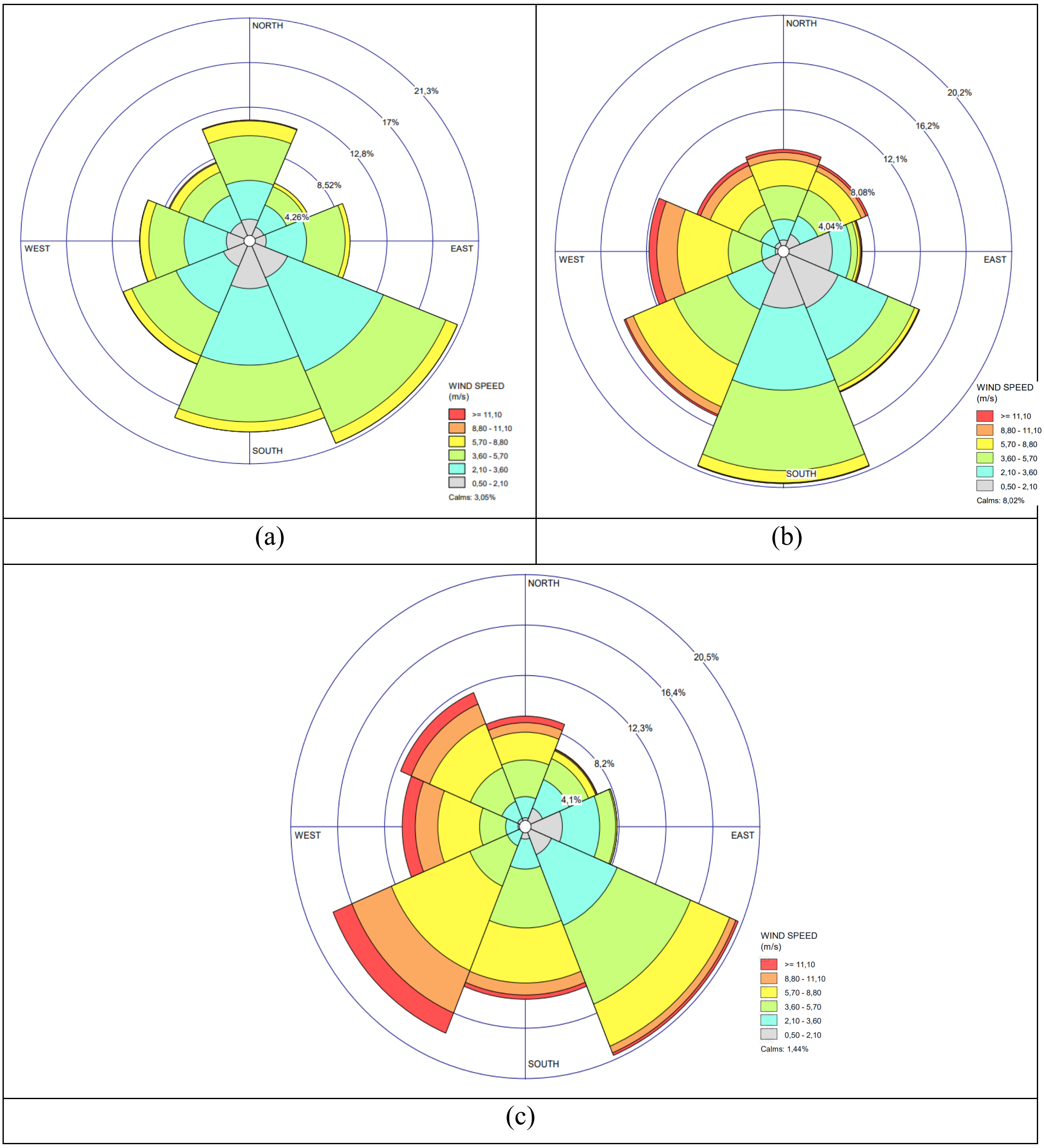

Figure 2. Wind distribution as recorded in Elbląg (a), Frombork (b)and Nowa Pasłeka © in years 2014-2020 (from the IMWM-NRI)

SIMULATION RESUTS

Numerical calculations using the DynaRICE model were carried out for variable wind conditions and the accompanying variable water levels in the sea, and the model domain are shown in figure 3. In the model the boundary conditions were set in the form of the water surface elevation at the sea and the water discharge on the rivers which are the tributaries of the lagoon and the sources of the fresh water. Ice conditions were set at the initial stage to be the ice cover with constant thickness. The thickness was set to be 0.2 m, which is commonly observed in the Vistula Lagoon. For modeling ice dynamics, cover was divided into uniformly distributed pieces, which were later subjected to move according to the force balance. Base on the ice contraction, free drifting floes with initial thickness or ice rubble with increased thickness and accumulated towards shore could be formed. The thickness of the ice floes will be added, causing ice accumulation, while the maximum concentration of 0.6 is reached (Table 1). The wind with speed of 12 m/s and directions of north-east and south-west were used for the simulations.

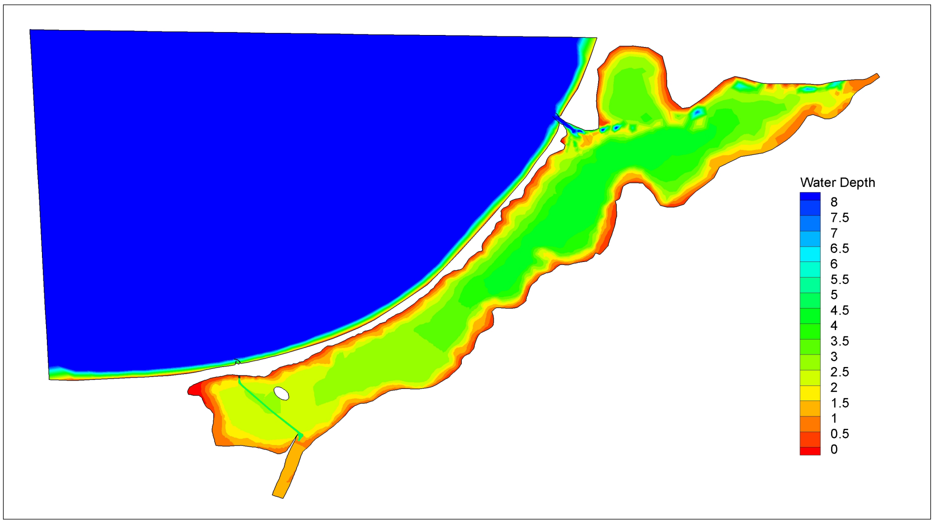

Figure 3. Model domain showing the water depth at the horizontal water level at 0.0 m (PL-EVRF2007-NH)

As a result of the wind blowing from the north-east at a speed of 12 m/s, the water level on the western shore of the lagoon is dynamically rising and the water level is gradually lowering in the area of the mouth of the Pregel River (Figure 4). The calculations showed that the maximum water level in such wind a condition in the region of the seaport of Elbląg is about 0.3 m above the initial sea level which is assumed at 0.0 m (reference level is: PL-EVRF2007-NH). In the case of the wind blowing at the same speed but from the opposite direction (south-western wind), the situation is reversed, i.e., the water level in the Polish part of the lagoon decreases, while in the Russian part it is rising. With such a wind condition, the water level in the port of Elbląg is reduced to a minimum level of about -0.9 m. The low water level is observed after 7 hours of wind action which drags water from the lagoon towards the sea (Figure 4). In the following hours, the wind causes further gradual dragging of water from the lagoon until reaching the water level of about -1.0 m after 24 hours. Pushing water into the lagoon is more dynamic and the high-water level in the seaport of Elbląg is visible after 5-6 hours of north-east wind action.

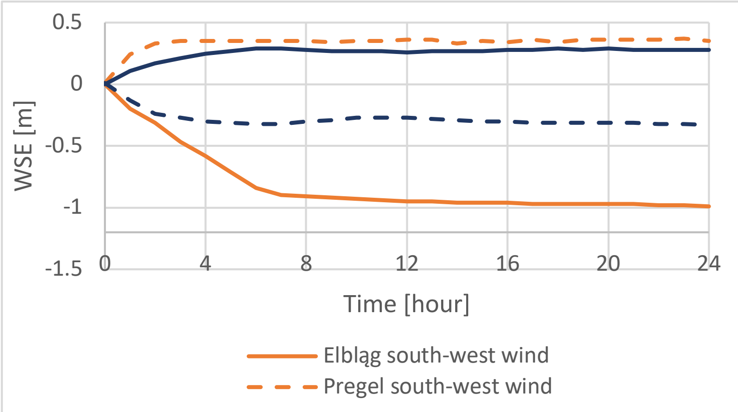

Figure 4. Calculation results for the water surface elevation in Elbląg and Pregel estuary for variable wind directions.

The ice floes followed the hydrodynamic conditions caused by the wind field, which can be seen in the results of ice dynamics calculations. In the case of a wind from the north-east direction, the ice moves towards the Polish part of the lagoon, building accumulations on the shores and on the new island (Figure 5). The thickness of the ice rubble that builds up on the shore of the island after 12 hours of wind action reaches locally 0.75 m, and after 24 hours it increases to as much as 0.9 m. The greatest ice thickness occurred on the easternmost shore, and the ice field which is stopped by the island, extending practically for the entire length of the lagoon. The reason is, there is no obstacle for the ice along the lagoon in the direction of wind action. The wind pushes the ice away from the southern breakwaters of the sluice on the split and it has no contact with them any longer during the simulation. The narrow distance between the island and the split (due to the concave shape of the split) does not allow ice to pass smoothly. Also, ice jam does not form along the convex shore of the split, where the inner harbor is located. For the south-western wind, considerable ice jam could be observed in the convex shore of the split, as shown below.

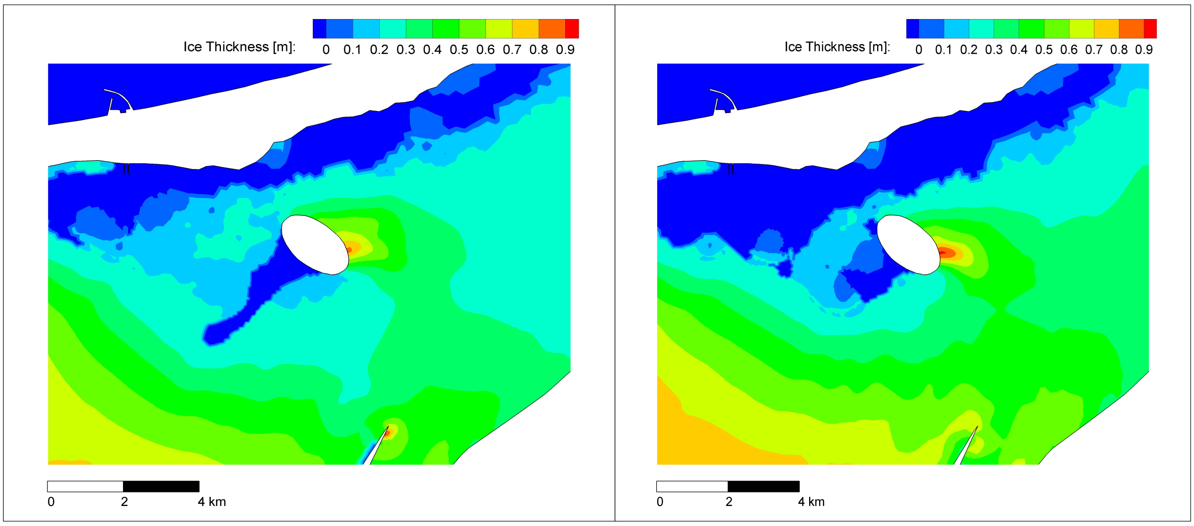

Figure 5. Numerical model results showing the ice thickness distribution on the Vistula Lagoon for wind blowing from north-east after 12 and 24 hours.

The south-west wind directs the ice to the Russian part of the lagoon. The moving ice rests on the eastern coast of the island, as well as on the southern shore of the spit and the newly built outer port (Figure 6). The area occupied by the ice piling up on the shores of the island and the spit is not significant, but the strong wind causes the ice to increase in thickness after 12 hours to almost 0.8 m. After another 12 hours, i.e., a full day of wind action with a speed of 12 m/s, the thickness of the ice did not increase. The results of the calculations showed that in the case of a small area from which ice is transported towards the island, the ice flows around the island and moves in a north-eastern direction, into the lagoon. It could be understood from the results that, during the beginning hours of the wind action, the ice is pushed from the westernmost part of the lagoon (about 6 -7 km long) towards the shores of the island. Furthermore, because of the direction of the wind, ice is shoved and increased in thickness at the edge of the island to 0.8 m. Although, with the continuation of the wind action, the ice flows away around the southern shore of the island in the direction of the wind. It decreases ice jam around the island. During the whole period of the wind action, ice stands along the split with not significant changes in its jamming condition.

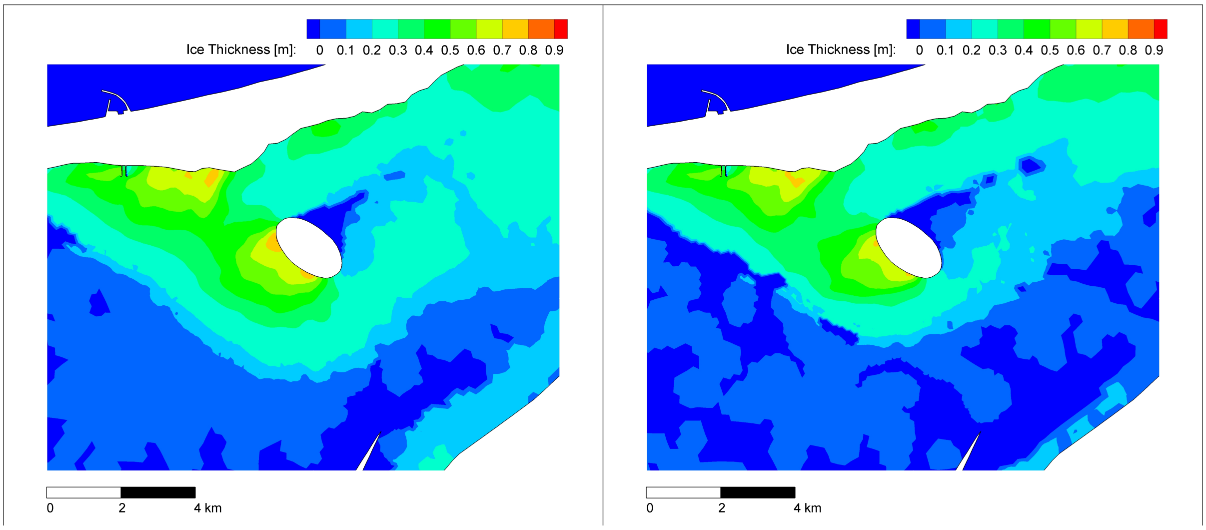

Figure 6. Numerical model results showing the ice thickness distribution on the Vistula Lagoon for wind blowing from south-west after 12 and 24 hours.

SUMMARY AND CONCLUSIONS

Numerical model simulation has been carried out to investigate the effect of the elements of the new shipping channel on ice dynamics in the Vistula Lagoon. The related variable conditions for the simulation were sea water level and wind velocity direction (obtained from three different stations from 2014 to 2022). The reason for using wind as the changing parameter is that it plays a crucial role in hydrodynamic status of the region. The boundary conditions were Baltic Sea water level and river discharge at the tributaries of the Vistula Lagoon (Figure 1). An ice cover with a thickness of 0.2 m was applied as the initial stage of the ice model, as uniform ice pieces. The ice cover would further change by the force of the wind magnitude of 12 m/s. The 12 m/s magnitude of wind was chosen for the simulation since in the range of strong winds it was the most probable magnitude to occur. The simulation results showed that wind and associated water surface elevation changes has the most significant impact on ice dynamics on the Vistula Lagoon. During the wind blowing along the lagoon from north-east or south-west direction, the ice will pile up over the shores of the artificial island which may cause significant load on the structure. The greater threat is posed by the wind blowing from the north-east due to the larger area from which the ice will be pushed towards the island. The inner harbor, located at the split, inside the lagoon, will also be affected by ice to a lesser extent than the island, but only in case of south western wind and.

The results showed both south western and north eastern winds (with the same magnitude of 12 m/s) lead to opposite trends for Polish and Russian parts of the Vistula lagoon. South eastern wind causes increasing and decreasing trends of the water level at the mouth of the Pregel river and western shore of the lagoon, respectively. Although, the mentioned decreasing trend in Elbląg estuary (for 2 hours) takes three times and a half long as much of the increasing trend in Pregel estuary (for 7 hours). These changes reach the water level in Elbląg and Pregel tributaries to -0.9 below and 0.3 above the water level. Afterwards, the water level more or less stagnated along the stretch of the lagoon .

The north eastern wind caused opposite directions for water level changes in 2 hours, to the same extent for eastern and western parts of the lagoon (increasing and decreasing trends, sequentially). These changes reach the water levels to 0.3 and -0.3 for western and eastern part of the Vistula lagoon, respectively. Even though, the changes levelled off after 2 hours for both parts of the lagoon.Apart from the calibration which has been done at the initial stage of the modelling, the simulation is not still validated. By the validation it means the final geometry of the new navigable channel to the port of Elbląg and observed ice condition as well as meteorological data to be applied in the simulation. Although, the DynaRICE model speaks for itself in the river ice dynamic and jamming simulation, based on the previous records. The use of this model for this specific study in Vistula lagoon showed it can be successfully used for the shallow water areas under the wind effect. The model implementation can be extended to other stagnated water bodies, e.g., shallow lakes and reservoirs as well as lagoons, mainly affected by the wind. The application is limited to the shallow water bodies since the two-dimensional DynaRICE model does not configurate the velocity distribution over large depths.

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