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Potential oil spills in the TSS Słupska Bank area – case study using the PISCES II simulator

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Abstract

The specificity of navigation in the Baltic Sea means that intensive ship traffic occurs on the main shipping routes. Therefore, there is a high risk of a collision that will result in an oil spillage; the Baltic Sea is an area that is very sensitive to this type of accident. In addition, there are sensitive Natura 2000 areas that require special protection. A case study of a potential oil spill in the Słupska Bank area has been carried out in this paper; the results of the oil spill simulations and their analyses are presented in this article. The simulations were carried out in the PISCES II oil spill simulator. The spread of oil pollutants in typical weather conditions, the size of the threatened areas and the oil's impact time have been analyzed. Based on the results obtained from the simulations, the most adverse weather conditions for the simulated oil pollution accident in the TSS Słupska Bank region have been determined.

Introduction

The Baltic Sea is a specific area that has a high ship traffic density. This traffic mainly occurs along the routes that result from the positions of ship traffic separation schemes and the distribution of the main ports in the Baltic Sea. The Traffic separation schemes (TSS) have been established in areas where, according to analyses of ships' routes, high density traffic is expected in order to increase the level of navigational safety in the vicinity of navigational dangers. Despite the similar levels of ship traffic, the quantity of transported cargo has increased. This means that larger ships are navigating in the Baltic Sea more often.

Ship traffic streams analyses (including HELCOM publications) have been carried out using AIS data in order to determine the collision risk in the Baltic Sea (HELCOM, 2018). Various analyses of accidents that have occurred in the Baltic region, including oil pollution, have been presented periodically in the literature; all of these activities are aimed at improving navigational safety.

Another problem is the proper location of anti-pollution resources in order to optimize their use in an oil pollution incident. Therefore, it is important to improve our knowledge of the speed and direction of the spread of oil pollutants in various weather conditions. This will enable the faster and more effective use of oil spill recovery units.

Analysis of ship traffic in the South Baltic

Ship traffic intensity data are mainly monitored on the basis of information from the AIS system. For this purpose, there are 13 reference lines that have been established in the Baltic; they allow the intensity of ship traffic streams to be monitored. In the case of the South Baltic, the South of Bornholm AIS passage line is the line that monitors ships equipped with the AIS system (Figure 1).

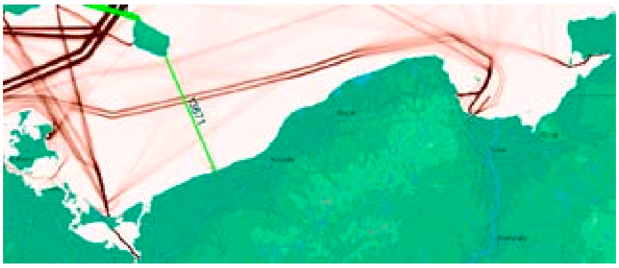


Figure 1. Ship traffic in the south Baltic area in 2017 (HELCOM data)

Based on many years of observations, it can be stated that the intensity of ship traffic in the Southern Baltic region has remained at a similar level in recent years (HELCOM data) – Figure 2. The percentage share of the most important types of ships in the same period is shown in Figure 3.

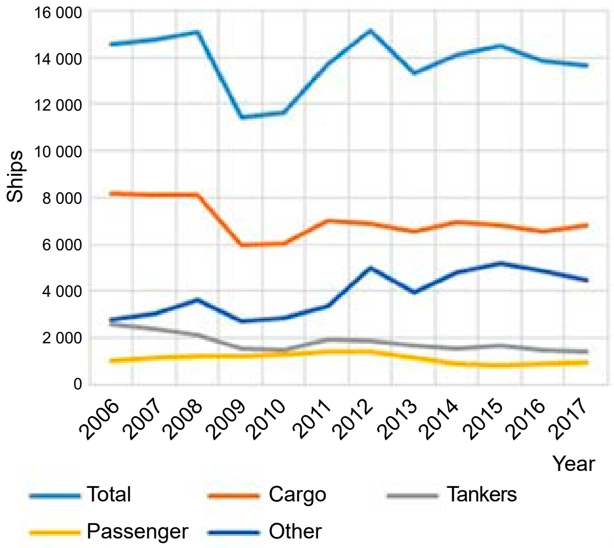


Figure 2. The number of ships crossing the South of Bornholm AIS passage line in 2006–2017 (HELCOM data)

It should be noted that the most intensive ship traffic to and from the ports of Gdańsk, Gdynia and Kaliningrad takes place on the route that resulted from the location of the traffic separation systems TSS Adlergrund and TSS Słupska Bank. However, based on the HELCOM data, it can also be seen that some ships navigate north of the Słupska Bank. They do not use the above-mentioned TSS routes and sail to other ports. Smaller ship traffic streams are connected to, or separated from, the main traffic streams (ships going to or from the ports of Szczecin/Świnoujscie) in the TSS Słupska Bank area. An additional factor that increases the ship traffic intensity is fishing and recreational vessels. The irregular nature of such navigation increases the risk of a collision, especially when they are sailing into a fishing area or

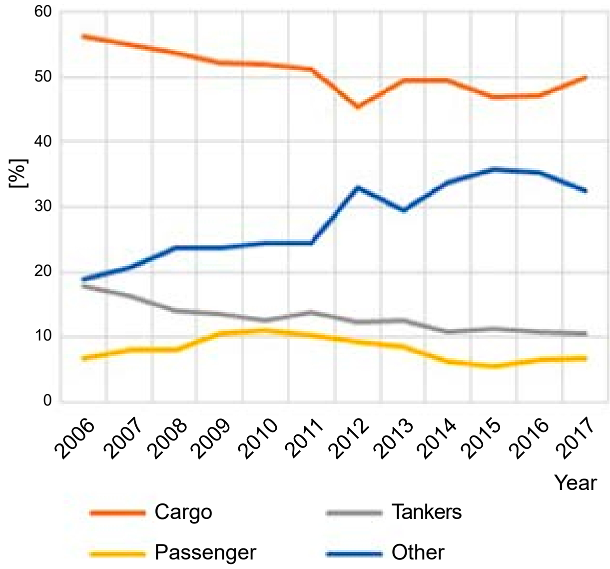


Figure 3. The percentage of the basic types of vessels crossing the South of Bornholm AIS passage line in 2006–2017 (HELCOM data)

returning to port (Anczykowska, Rekowska & Ślączka, 2017); the ports of Łeba, Ustka and Kołobrzeg are ports of this type in the TSS Słupska Bank area.

The planned development of offshore wind energy in the South Baltic area is another factor that may have an impact on traffic safety in the TSS Słupska Bank area in the future. Planned or implemented investments will be located north of the TSS and Słupska Bank. Therefore, an increase in the intensity of support and service ship traffic should be expected at both stages of the wind farms' construction and operation.

Oil spill simulation

Oil spill models can be used in two ways: models that work on the basis of real observations and measurements for conducting a related impact or risk assessment, and models that are based on modeled simulations to estimate the potential locations of spills and the impact results (Nelson & Grubesic, 2017).

However, for both types of simulations, the most important data are the information about the currents and tides within the area of interest. For this purpose, both actual and forecast data are used, as well as multi-year average values. Wind direction and strength data, as well as other meteorological data (waves, temperature, etc.) that affect the behavior and degradation of oil pollutants are equally necessary. Aside from this baseline information, oil spill models require data on the spill type, location, duration, depth, quantity and the coefficients for horizontal and vertical diffusion. More advanced spill models should consider surface and/or subsurface oil transport and the calculations of its evaporation, dissolution, entrainment, emulsification, biodegradation, and the sediment–oil interaction. All these processes and the models that are used have been described in detail in many publications (ITOPF, 2011; Fingas, 2011; 2913; Soltanpour, Wijayaratna & Hajisalimi, 2013; Hook et al., 2016; Toz, Koseoglu & Sakar, 2016; Li, 2017; Kastrounis, 2018).

There are many different spill simulation packages and oil spill models that are used. Some of them simulate the behavior of oil using a Lagrangian model or a boundary fitted grid technique. Most of the early models were two-dimensional; they mostly concentrated on the surface movement of oil (Li, 2017). Nowadays better algorithms for oil transport have been implemented and more accurate ocean and atmospheric models are used to calculate the behavior of oil spills. Such simulation packages include: ADIOS2 (Automated Data Inquiry for Oil Spills), GNOME (General NOAA Operational Modeling Environment), OILMAP/SARMAP (Search & Rescue Model and Response System), SEATRACK WEB, OILTRANS and PISCES II. Detailed descriptions of the algorithms that are used and comparisons of the simulation packages can be found in numerous publications, e.g. (Berry, Dabrowski & Lyons, 2012; Toz, Koseoglu & Sakar, 2016; Li, 2017; Kastrounis, 2018; Toz & Koseoglu, 2018). Due to the fact that the analysis of the algorithms is not the subject of this article, the nuances of the mathematical models that are used will not be covered here.

However, given the geographic diversity of the marine environments and the limitations of the models in general, there is no single "best" model that could ever be 100% accurate, nor is there any definitive combination of the data that should be used for modeling the risk and the impacts of an oil spill (Nelson & Grubesic, 2017).

The characteristics of the research area

TSS Słupska Bank

The TSS Słupska Bank and the Vessel Traffic System (VTS) VTS Słupska Bank was created in accordance with regulation 10 of chapter V of the SOLAS IMO Convention (IMO, COLREG.2/Circ.61, MSC.87) and has been in force since December 1, 2010 (Maritime Office in Słupsk, 2010). The regulations were updated and the scope of the duties of the VTS Słupska Bank was specified in 2018 (Maritime Office in Słupsk, 2018).

The TSS was created to increase ship traffic safety and to improve environmental protection by separating the two opposing ship traffic streams. The system consists of two lanes and a zone between them enabling intersection of the system and navigation towards the port of Ustka. The width of the lanes is 1.75 NM and the width of the separation zone is 0.5 NM. The TSS is located between Słupska Bank and the coastal traffic zone. The range of the TSS Słupska Bank is marked in the figures presenting the results of the oil spill simulations (Figures 9 and 10).

Natura 2000 areas

Due to its specificity, the Baltic Sea is very sensitive to all kinds of pollution. Therefore ecologically sensitive areas have been created within the Natura 2000 system in the Baltic Sea area for better sea and coastal areas protection. The following ecologically sensitive areas are located in the TSS Słupska Bank region (Ministry of Climate, 2011):

- Przybrzeżne wody Bałtyku (PLB990002) stretches along the Polish Baltic coast in the Polish sea areas, covering an area of 194,626.7 ha;
- Ławica Słupska (PLC990001) covers the Ławica Słupska area and it is located north of the TSS, covering an area of 80,050.3 ha;
- Pobrzeże Słowińskie (PLB220003) is located in the municipalities of Łeba, Główczyce, Smołdzino, Ustka and Wicko, covering an area of 21,819.5 ha.

The ranges of the particular areas have been plotted on the chart that was used during the simulation and they were used to determine the oil pollution impact time of the borders of the area. The borders of the Natura 2000 areas are shown in the figures presenting the results of the oil spill simulations.

The characteristics of the hydrometeorological conditions

Winds

The direction of the winds mainly depends on the current atmospheric circulation; local conditions affect their speed and direction in the coastal zone. The frequency of the winds is presented in Figure 4 and has been divided into the seasons of the year (expressed in %) based on many years of observations (Sailing Direction of the Baltic Sea, 2009).

The statement of the wind directions indicates that, in the first and the fourth quarter of the year,

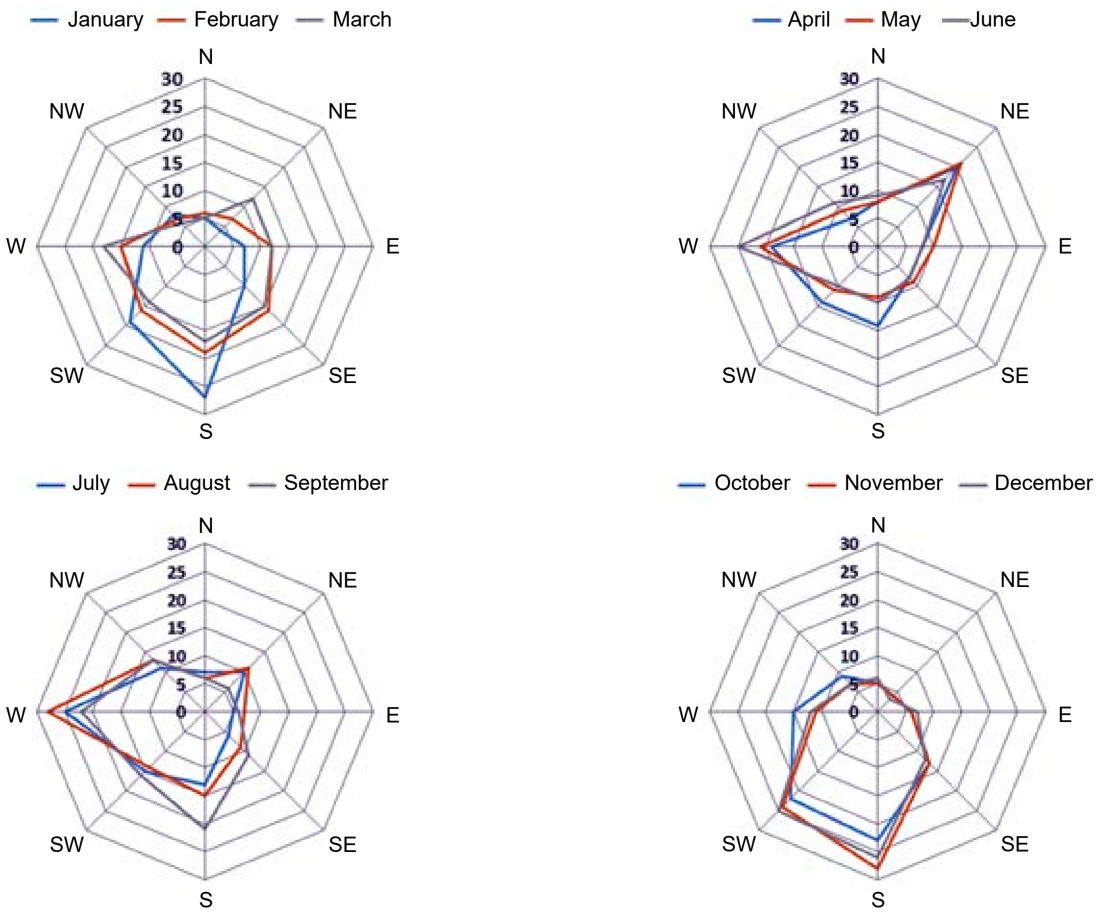


Figure 4. Average frequency of the wind direction in the area of the port of Ustka, divided into the seasons of the year (Sailing Direction of the Baltic Sea, 2009)

winds from the south and south-west prevail, while in the remaining quarters, westerly winds are most often observed. The high frequency of northeast winds in the April to June period can also be seen.

The average wind speed that occurred in the area considered is about 4–5 m/s. The strongest winds occur in the September to March period; winds exceeding 7°B or more occur most often in January (Figure 5).

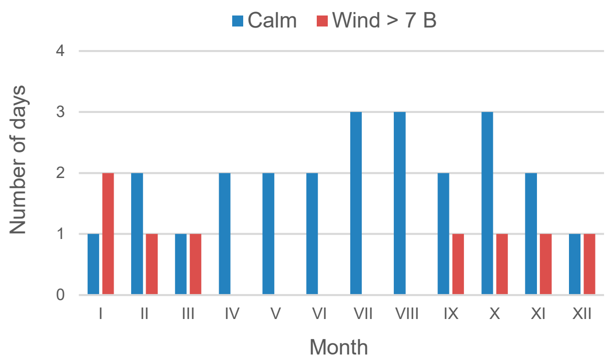


Figure 5. Average number of days without wind and with winds of 7°B and above throughout the year near the port of Ustka (Sailing Direction of the Baltic Sea, 2009)

Currents

In stable weather conditions and with low winds, there are constant Baltic currents in the area. This means that the water circulates in a counterclockwise direction. In this case, the currents flow eastwards towards the southern Baltic coasts, but their speed generally does not exceed 0.2 kn.

The system of surface currents is disturbed by strong winds; in open water, the direction of the current is then directly related to the direction of the wind and deviates from this direction by about 20–30 degrees to the right. The directions of the currents are additionally modified by the shape of the shoreline in coastal areas.

It is not possible to accurately predict the distribution of the direction and speed of the currents in the described area due to the large impact of the local and actual meteorological conditions. However, during good and stable weather, there are generally weak currents towards the east at speeds of about 0.1–0.3 knots which may occasionally reach higher speeds (up to 0.9 kn).

There are usually small waves (summer and October) in the Polish coastal zone; intermediate and large waves occur most often in late autumn and winter. The occurrence of large waves depends primarily on the duration of the storms, as well as the strength and direction of the wind (this most often occurs during winds blowing inland).

Visibility

There are 55 days on average during the year where there is restricted visibility near Ustka. The number of days with fog increases in autumn, winter and early spring. The number of days with restricted visibility is presented in Figure 6.

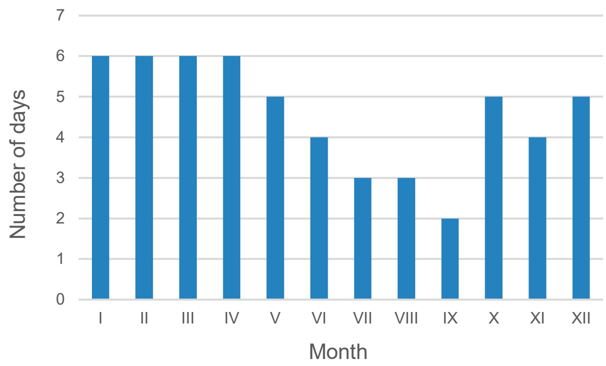


Figure 6. The average number of days of restricted visibility in the vicinity of the port of Ustka (Sailing Direction of Baltic Sea, 2009)

Simulation assumptions

Oil spill simulations were carried out using The Potential Incident Simulation, Control and Evaluation System (PISCES II). This is a specialized simulator that enables the simulation of the behavior of an oil spill in water (spreading, evaporation, dispersion, emulsification, viscosity variation, burning), as well as the influence of wind and currents on the oil pollution and the oil's interaction with booms, skimmers and the coastline. It is possible to record many parameters during the simulation for later analysis and to draw conclusions.

The following factors are taken into consideration in the math model (Pisces2, 2007; Pisces II, 2008):

- environmental parameters: coastline, field of currents, weather conditions, wave height and water density;
- physical properties of the spilled oil: specific gravity, surface tension, viscosity, distillation curve and emulsification characteristics;
- properties of the sources of the oil spill;
- human response actions: booms, on water recovery, application of chemical dispersant.

The results of the simulations that were carried out in the past using the PISCES II simulator have been presented at multiple international conferences and published in the literature (Delgado, Kumzerowa & Martynov, 2006; Perkovic & Sitkov, 2008; Łazuga, Gucma & Perkovic, 2013; Jarząbek & Juszkiewicz, 2016; Toz & Koseoglu, 2018). The software has been used to simulate real events for many years and has become respected in the oil spill software industry thanks to the high reliability of its solutions (Delgado, Kumzerowa & Martynov, 2006; Perkovic & Sitkov, 2008; Toz & Buber, 2018). This has proven the high usefulness of the PISCES II simulator in this field.

PISCES II could be used also to train people to take action to combat an oil spill. For this purpose, it could be coupled with other simulators or systems (Perkovic & Sitkov, 2008).

Position of the accident

After the analysis of the navigational conditions, it was assumed that an accident resulting in an oil spill would occur in the position between two parts of the TSS Słupska Bank (accident position: φ = 54°48.59' N, λ = 016°51.53' E). In this area, eastgoing vessels can meet in a crossing situation with both fishing vessels and ships leaving/entering the port of Ustka. Crossing traffic could be also associated with planned wind farm investments in the future.

Simulated oil spill characteristics

It was assumed that about 15 tons of ARABIAN LIGHT oil leaked into the sea within an hour as a result of the accident (the oil's properties are presented in Table 1).

According to the National Contingency Plan, an oil leak of this size can be considered as a local/regional incident, the effects of which should be controlled with the use of local units and resources (National Contingency Plan, 2005).

Weather conditions

The main current direction was simulated as corresponding to the usual conditions in this part of the Polish coast (in the TSS area, an eastward current with a speed of 0.25 kn – Scenario 1). Of course, the simulated current field, close to the coast, also depends on the depth and shape of the coastline. Additionally, in order to determine the influence of the current's speed on the behavior of the oil

Table 1. Properties of the oil spill (Pisces II, 2008)

Name	ARABIAN LIGHT	Distillation curve	
		Temperature	Fraction
Density	0.858 g/cm^3	60°C	2%
Surface tension	16.8 dyn/cm	100°C	7%
Viscosity	16.3 cSt	140°C	12%
Maximum water content	87%	200°C	22%
Emulsification content	0%	250°C	31%
Pour point	–53°C	300°C	40%
Flash point	–20°C	350°C	49%
		400°C	57%

pollution, the next set of simulations was carried out at a simulated current speed of 0.5 kn (Scenario 2).

Eight simulations of wind variants were implemented for each scenario to determine the effect of the wind. The scenarios differed from each other in the main direction of the wind, which was changed by 45° each time (N, NE, E, SE, S, SW, W, NW) and its variability was also simulated within ±10°; it was assumed that the wind force would be constant. The wind speed was equal to 18 kn (5°B) with a corresponding wind wave height of 2 m. The long-term effect of the wind on the directions of the current was not simulated.

Simulation results and analysis

The behavior of the oil spill during the simulation

The results that were recorded during the simulations that were carried out allowed for the impact of the hydrometeorological conditions on the route of the simulated oil pollution and changes in the structure of the pollution to be determined. The change in the amount of drifting oil over 24 hours of the simulation for both scenarios is shown in Figure 7 and the change in the size of the polluted area is shown in Figure 8.

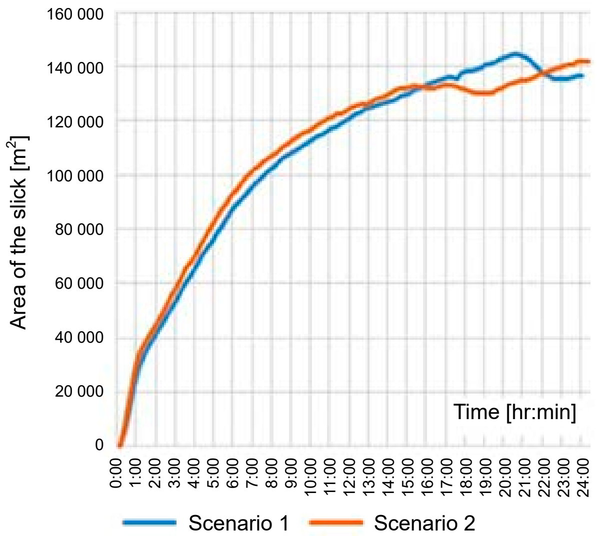


Figure 8. The average recorded area of the oil slick (scenario 1 and 2)

The recorded results led to the conclusion that an increase in the simulated current speed hardly affects the acceleration of the degradation of the oil pollution (there is a difference of between 3.2–2.1% of the amount of drifting oil between the results of the 1st and 2nd scenario) or the increase of the polluted area (a difference between 11.9–3.6% in the first 24 hours of the simulation). The shape of the oil pollution also depends on the wind direction in relation to

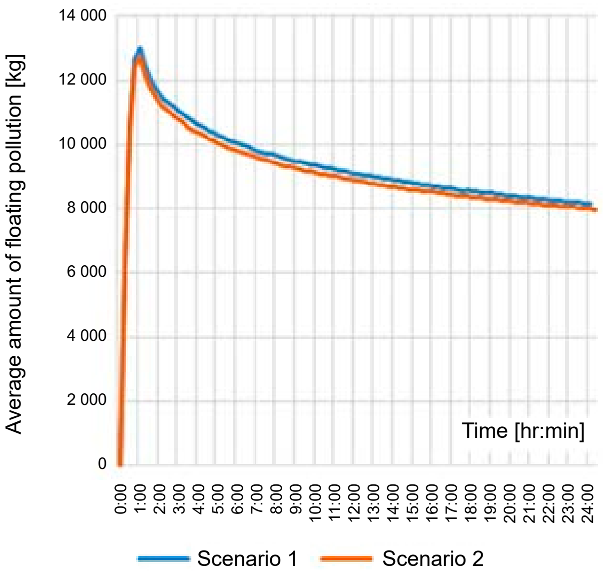


Figure 7. The average amount of floating oil pollution (scenario 1 and 2)

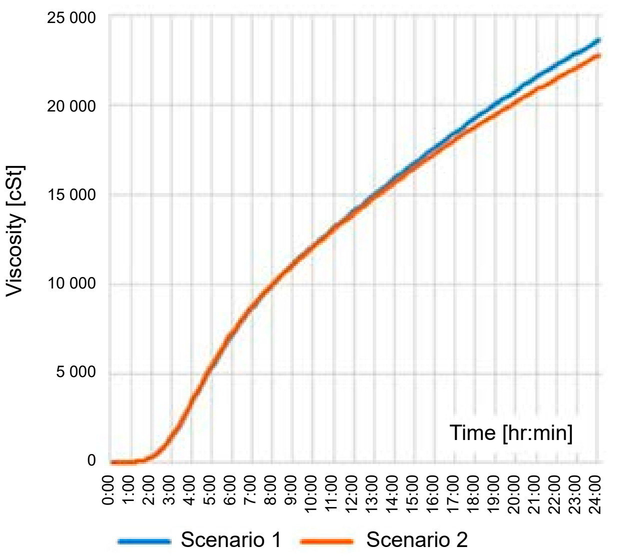


Figure 9. The average change in the viscosity of the oil during the simulation (scenario 1 and 2)

the current direction. Changes in the flow rate and the amount of pollution also increased the viscosity. After 24 hours of the oil spreading, the average viscosity values (for scenarios 1 and 2) differed by 3.5% (Figure 9).

Determining the probable area of the oil pollution

The position of the front edge of the oil spill was recorded at 4 hour intervals during all of the simulations to determine the probable area of the oil pollution. This allowed the maximum boundaries of the areas of which the pollution can reach at different simulated wind directions and speeds, as well as wave height and current strength, to be determined. The routes of the pollution that were recorded during the simulation are shown in Figure 10.

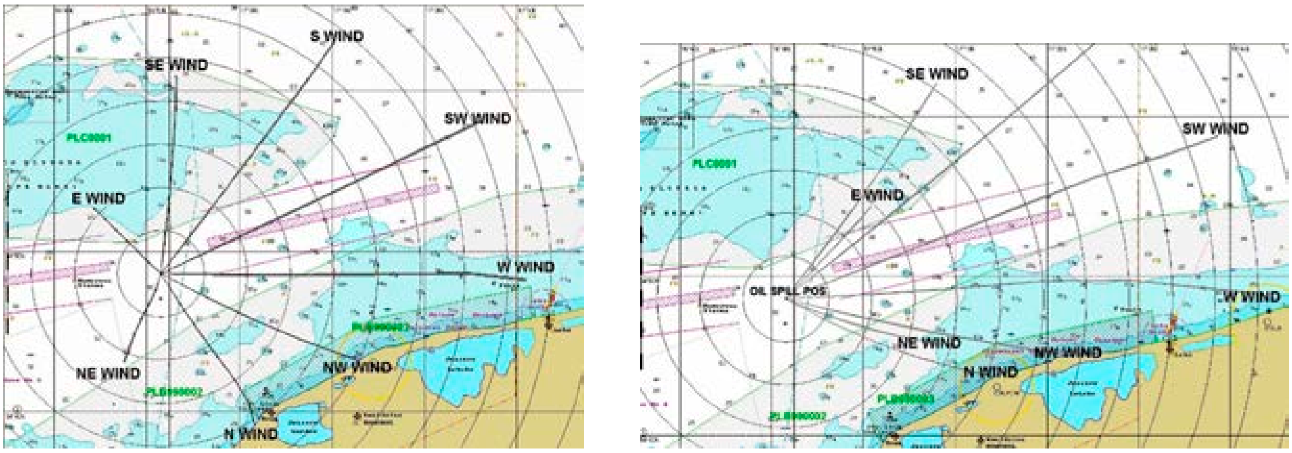
The potentials areas of oil pollution were determined on the basis of data containing information about the drift of oil pollutants during the simulation. The boundaries of the thus defined potential areas of pollution over 20 hours of observation are shown in Figure 11. This approach allows the parts of the coastline that are threatened by pollution at a given time to be ascertained.

Impact time for the borders of the protected areas

The times when the oil pollution reached the boundaries of the protected areas and the coastline were also recorded during the simulations. The collective results from all of the simulations are presented in Table 3.

Analysis of the simulation results

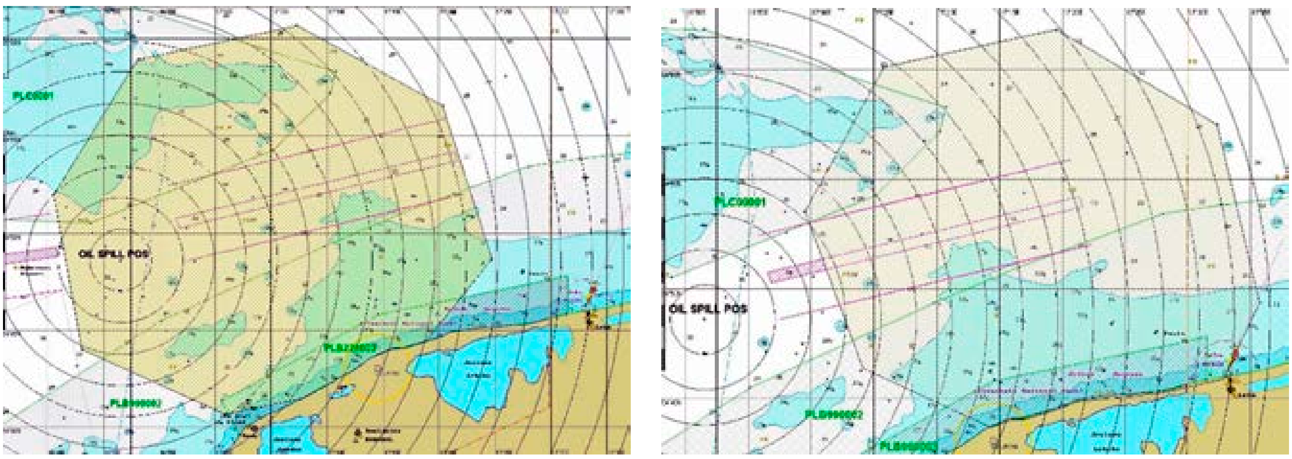
The analysis of the results that were obtained during the simulations (directions and speeds of the movement of the oil spill) allowed both the dangerous and safe sectors of the wind directions to be determined for the protected areas. The analysis only applies to the oil spills that were described above in



Scenario 1

Scenario 2

Figure 10. Oil pollution routes for different wind directions



Scenario 1

Scenario 2

Figure 11. Potential borders of the area of oil pollution for different wind direction recorded over 20 hours of the simulation

Table 3. The impact time and the amount of the oil pollution crossing the borders of a sensitive area

Wind direction	Area name	Scenario 1 (current E/0.25 kn)		Scenario 2 (current E/0.5 kn)	
		Oil impact time [h:m]	Oil pollution floating/stranded [t]	Oil impact time [h:m]	Oil pollution floating/stranded [t]
N	PLC990001	no impact	0	no impact	0
	PLB990002	06:56	9.8	06:05	9.3
	PLB220003	no impact	0	09:03	8.6
	Coastline	24:20	8,0	18:53	6.8
NE	PLC990001	no impact	0	no impact	0
	PLB990002	14:50	8.0	14:05	8.8
	PLB220003	no impact	0	31:20	7.7
	Coastline	64:19	6.6	43:30	6.6
E	PLC990001	11:00	9.5	no impact	0
	PLB990002	no impact	0	no impact	0
	PLB220003	no impact	0	no impact	0
	Coastline	no impact	0	no impact	0
SE	PLC990001	05:00	10.2	06:02	9.7
	PLB990002	no impact	0	no impact	0
	PLB220003	no impact	0	no impact	0
	Coastline	no impact	0	no impact	0
S	PLC990001	06:05	9.6	07:25	9.4
	PLB990002	no impact	0	no impact	0
	PLB220003	no impact	0	no impact	0
	Coastline	no impact	0	no impact	0
SW	PLC990001	no impact	0	no impact	0
	PLB990002	no impact	0	no impact	0
	PLB220003	no impact	0	no impact	0
	Coastline	no impact	0	no impact	0
W	PLC990001	no impact	0	no impact	0
	PLB990002	09:20	9.3	07:44	9.4
	PLB220003	no impact	0	no impact	0
	Coastline	33:00	7.7	28:27	7.7
NW	PLC990001	no impact	0	no impact	0
	PLB990002	06:00	9.9	05:14	9.8
	PLB220003	14:05	8.8	11:45	8.8
	Coastline	17:26	8.5	25:44	8.4

Area name: PLC990001 – Ławica Słupska; PLB990002 – Przybrzeżne wody Bałtyku; PLB220003 – Pobrzeże Słowińskie.

a strictly defined location. The sectors have been designated separately for each scenario and are as follows:

For scenario 1 (E/0.25 kn current):

- The safe wind directions are within 060–075° and 205–250°. For such winds, the pollution will drift along the existing TSS and will not violate the boundaries of the Ławica Słupska and the Przybrzeżne wody Bałtyku areas. The small range of angles for the first sector is due to the opposing wind and current directions and the associated low drift speed of the oil pollution.
- The sector of the winds from 075–205° contains the most unfavorable wind directions for the Ławica Słupska area. In these circumstances the pollution will move into the protected area. The time it took to reach its border depended on the difference in the current and wind directions and varies from about 11 hours (winds from 100° and 205°) to 5 hours (wind from 135°).
- The Przybrzeżne wody Bałtyku area was threatened by winds from the directions 250–055°.
- The Pobrzeże Słowińskie area was threatened by the winds from the directions 270–000°.
- The coastline may be polluted with winds from 265–050°; the pollution will reach the shore the fastest with winds in the range of 315–000° (17–24 hours).

For scenario 2 (E/0.5 kn current):

- The safe wind directions are within 065–080° and 185–245°. These wind directions are safe for the protected areas and the coastline in this scenario.
- The directions in the range 080–185° are the most unfavorable wind directions for the Ławica Słupska area. In these cases, the pollution will move along the eastern edge of Ławica Słupska. The time taken for the pollution to reach its border depends on the difference between the current and wind directions and changes from about 8 hours (wind from 185° direction) to about 4 hours (wind from 135° direction).
- The Przybrzeżne wody Bałtyku area is threatened by the winds from the directions 245–065°.
- The Pobrzeże Słowińskie area is threatened by winds from the directions 285–060°.
- The coastline may be polluted with winds from 270–060°; the pollution will reach the shore the fastest with winds in the range 315–000° (17–24 hours).

The described wind sectors are shown in Figure 12.

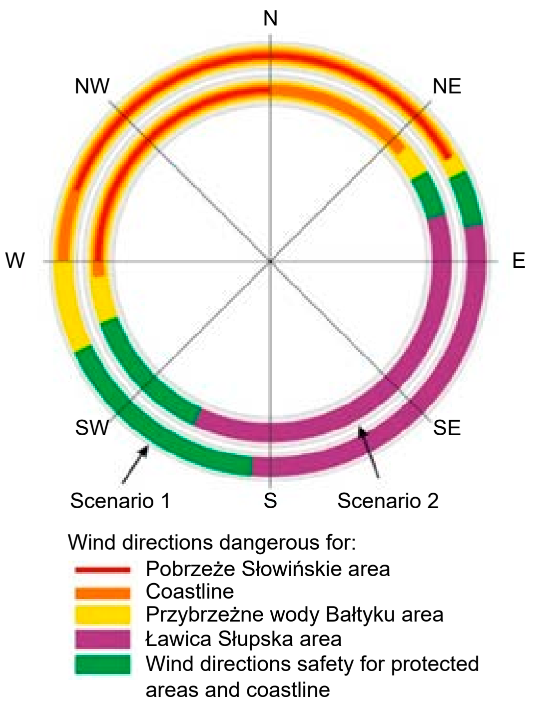


Figure 12. Summary of the safe and dangerous wind directions for the protected areas

The comparison of the safe wind sectors (Figure 12) with the typical wind directions that are recorded in this area in particular yearly periods (Figure 4) and the average annual values (Figure 13) have led to the conclusion that safe winds directions are usually found in the Słupska Bank area (there is over a 50% probability of the occurrence of wind in the S-SW-W sector during the year and near 17% probability of SW winds).

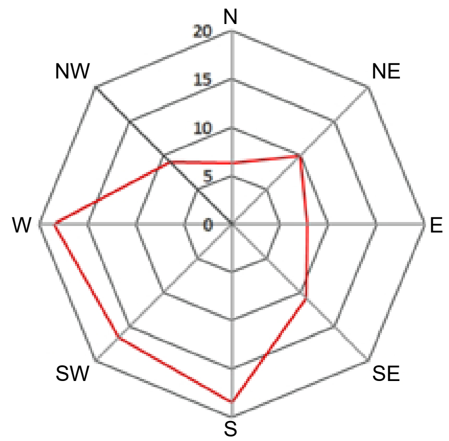


Figure 13. Average frequency of the wind direction in the area of the port of Ustka during the year [6]

Conclusions

In this paper, the results that were recorded during the simulations of an oil spill in the Baltic Sea allowed the following to be determined:

- the most unfavorable wind directions at which pollution can move into protected areas, as well as contaminating the seashore;
- the safe winds sectors at which the oil pollution will spread towards the open sea without affecting the boundaries of the protected areas and resulting in the extension of the possible time to start anti-pollution actions;
- the estimated time when the oil pollution will reach the borders of the protected areas.

It should also be remembered that the simulations that were carried out relate to a specific situation that depends on the position of the oil spill, the type of spilled oil and the current field that is typical for the research area. Changing any of these parameters can significantly affect the results of the simulations.

The available analyses of the impact of the weather conditions on the behavior of oil pollution in a specific sea area can be used in the process of planning anti-pollution action. Proper allocation of the appropriate resources will be easier if there is a forecast of the predicted routes of the oil pollution and the drifting time for it to reach critical areas is defined.

Of course, the effectiveness of anti-spill measures also depends on how quickly they commence.

It is always much cheaper to remove oil pollution in the open sea than when it has reached the shoreline.

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