the International Journal on Marine Navigation and Safety of Sea Transportation
http://www.transnav.eu
Volume 18
Number 4
December 2024
DOI: 10.12716/1001.18.04.14

Environmental Impact of the Oil Spill Caused by the Leakage of the Exemplary Pipeline in the South Baltic Sea

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ABSTRACT: A significant spillage of oil-derived cargo or fuel in the port areas causes serious threats to the natural environment and to the ship traffic. Hydrometeorological conditions and the availability of means to limit such spillage have a significant influence on the way the oil spill propagates. In the article, the authors presented a simulation of the distribution of oil spills taking place in Port Polnocny in various hydrometeorological conditions and the impact of the spill on areas located near the port. For simulation process was used GNOME an interactive environmental simulation system designed for the rapid modelling of pollutant trajectories in the marine environment.

1 INTRODUCTION

The total volume of oil lost to the environment from tanker spills in 2022 was approximately 15,000 tonnes; more than 14,000 tonnes of which was lost in the three large incidents. This figure is higher than the previous three years but remains a fraction of the 2.95 billion tonnes of crude oil and petroleum products that are transported by sea each year. [11]

The tendency of number of oil spill gradually decreased and last 10 years seems to stabilize on the same level – average 6. See figure 1.

ITOPF has recorded tanker spill statistics over the last 50 years and in this time, despite some annual fluctuations, the number and volume of oil spills from tankers has dropped dramatically. These numbers are stabilising at a low level, with the reduction being driven by positive change from the shipping industry and supported by governments. Accidents, other than shipping sources, such as pipeline spills and oil industry activities, as well as natural seepage, also contribute towards the global input of oil into the marine environment. [11]

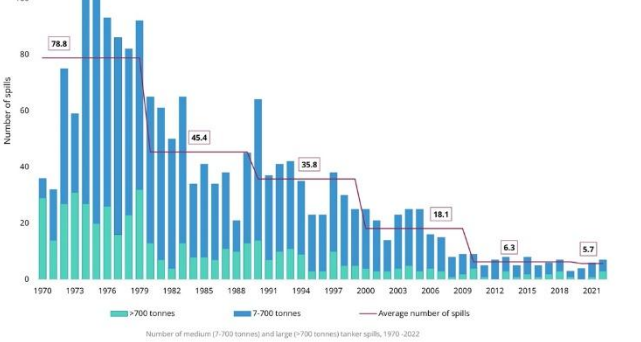

Figure 1. Quantity of Oil spill Tanker 1970-2021

The Baltic Sea is almost surrounded by land and therefore sources of marine pollution are located mainly on the land. Another paradox relates to shipping traffic intensity and maritime accidents. The Baltic Sea is characterised by the large shipping traffic, but the last decades' data show only more than 100, usually insignificant and minor, accidents and incidents at the Baltic Sea every year. [7]

In the last few years, the development of port terminals in the North Port of Gdansk – Deepwater Container Terminal & Oil Terminal has resulted an increase ship traffic in area of the Gulf of Gdansk.

Due to present the geopolitical situation of the recent months, the delivery of the raw material - crude oil for fuel production in refinery - is carried out basically only through the Oil Terminal. This year will be record-breaking in terms of the number of crude oil tankers calling at the Oil Terminal as well as transhipments and the amount of transhipped crude oil.

Figure 2. Oil Terminal in Gdansk Port Polnocny - Transas Simulator.

The location of the Oil Terminal and the safety of crude oil handling operations mean that it has a significant impact on the safety of other port terminals as well as tourist areas located on the Vistula Spit – Figure 2.

During cargo handling operations between the crude oil tanker and the oil terminal, an oil spill may occur. The weakest link in this process seems to be the ship-to-terminal connection or the failure of the pipeline and valve system at the oil terminal. [1]

The article assumes one of the most probable scenarios related to the interruption of the pipeline continuity and the leakage of the pipeline contents after an emergency stop of handling operations.

Figure 3. Place of the incident – GNOME [2]

Figure 3 shows the location of the failure causing the most unfavourable situation, a pipeline rupture, which will cause leakage of the contents of practically the entire transfer pipeline with a length of about 1 km.

2 MATERIALS AND METHODS

The amount of crude oil that could be released into the sea depends mainly on the pressure of the reloaded raw material and on the transhipment rate, which can reach even 10,000 cbm/h, which gives 2,5 cbm/s. [1]

Performed 60 hours of the simulation with wind force 4°B variable from WSW to WNW (with uncertainty 3%), wind's direction changed every 12 hours.

For the simulation scenario, it was assumed that an amount of crude oil corresponding to the content of the unprotected pipeline for 10 minutes continuously discharging was released into the Gulf of Gdansk.

Simulations were carried out based on the GNOME application. GNOME, version 1.3.5, is an interactive environmental simulation system designed for the rapid modelling of pollutant trajectories in the marine environment. [3]

The overall design is that of modular and integrated software. Inputs to GNOME include:
- maps of areas,
- bathymetry,
- numerical circulation models,
- location and type of the spilled oil,
- oceanographic and meteorological observations, and
- other environmental data.

2.1 *Maps of area*

GNOME is not specific for any particular region and no specific shoreline is built in. Application accepts two different types of maps: one with shoreline data in the form of boundary file atlas (BNA) maps (such as those produced by GOODS, the other with grid boundary data and bathymetry to create pseudo three- dimensional (3-D) maps. [3]

The user must download a map via GOODS' "Map generator" tool or create a map to run a scenario. Each map is rasterized into a land/water bitmap for the purposes of tracking the oil beaching. The land/water bitmap is of finite resolution, so it doesn't exactly match the map outline.

2.2 *Movers in simulation area*

Movers are any physics that cause movement of the oil parcel in the water – generally currents, winds, and diffusion. Universal movers apply everywhere, and usually consist of wind and diffusion. To get the overall movement the u (east-west) and v (north-south) velocity components from currents, wind, diffusion, and any other movers are added together at each time-step, i, using a forward Euler scheme. The movers are given a point (x, y, z, t) and return a displacement (Δx, Δy, Δz) at t - Equation 1-3. Calculation of zonal, meridional, and vertical displacement by movers. [3]

$$\Delta x = \frac{u \times \Delta t \times \cos y}{111120,00024} \tag{1}$$

$$\Delta y = \frac{v \times \Delta t}{111120,00024} \tag{2}$$

$$\Delta z = 0 \tag{3}$$

where:
$\Delta t = t - t_1$ is the time elapsed between time-steps i;
y is the latitude in radians;
111,120.00024 is the number of meters per degree of latitude (assumes 1' latitude = 1 nautical mile everywhere); and
Δx, Δy are the 2-D longitude and latitude displacement, respectively, at the given depth layer z. At present, movement in GNOME cannot occur between depth layers (thus the vertical displacement, Δz, is held at zero).

The calculation of total movement is a simple vector addition of the displacement of a given pollutant particle by each mover over the time-step.

2.2.1 *Winds in simulation area*

GNOME allows several different wind movers – constant, time-dependent, and time/space dependent. Table 1 includes constant wind speed in range 12.9-15.3 kn (force 4°B scale) and directions which are changed every 12 hours according to track of most probably the low-pressure over the simulation area. [3]

Table 1. Wind parameters during simulation.

Date & time	Wind speed [kn]	Wind direction [°]
2022/05/29 00:00:00	12.9-15.3	247.50
2022/05/29 12:00:00	12.9-15.3	258.75
2022/05/30 00:00:00	12.9-15.3	270.00
2022/05/30 12:00:00	12.9-15.3	281.25
2022/05/31 00:00:00	12.9-15.3	292.50

2.2.2 *Currents in simulation area*

On simulation area doesn’t exist any constant ocean or tidal currents. In situation when the wind direction is constant for long time wind-driven current is created. Its parameters mainly depend on the force and direction of the wind.

The current components can be scaled linearly by wind speed or by the square of wind speed (i.e., wind stress) or if no historical winds are available (or the wind record is insufficient to satisfy the selected time over which to average) the model can be set to extrapolate and will use whatever wind is available until enough data are accumulated.

Currents move the oil around and are defined on a particular grid. GNOME recognizes finite element, rectangular, and curvilinear grid circulation models.

For standard mode locations generally in USA, files are used from CATS hydrodynamic model (Current Analysis for Trajectory Simulations). The CATS model is a 2-D depth-averaged steady-state finite element circulation model. [3]

2.2.3 *Diffusion of crude oil*

For simulation purpose was used crude oil, typical to this one which is delivered to Oil Terminal in Gdansk. Medium Crude Oil properties contain the Table 2 below.

Table 2. Generic Medium Crude Oil properties.

Properties	Value & units
API	29.70
Standard Density at 15°C	878.0 [kg/m3]
Flash Point	+8.60°C, (-13.00°F)
Pour Point	+14.00°C, (-10.00°F)
Emulsification Constant	0.04

Random spreading - diffusion, is done by a simple random walk with a square unit probability. The random walk is based on the diffusion value D, set in the model which represents the horizontal eddy diffusivity in the sea water. The D value could be changed in range 1,000 – 1 000,000 cm2/s. In GNOME diffusion and spreading are treated as stochastic processes.[3]

$$\frac{\partial C}{\partial t} = D_x \times \frac{\partial^2 C}{\partial x^2} + D_y \times \frac{\partial^2 C}{\partial y^2} \tag{4}$$

where:
C is the concentration of a material;
D are the scalar diffusion coefficients in the x and y directions;

Diffusion can be simulated with a random walk with any distribution, with the resulting diffusion coefficient being one-half the variance of the distribution of each step divided by the time-step - Equation 5. [3]

$$D_x = 0,5 \times \frac{\sigma^2 x}{\Delta t} \tag{5}$$

For simulation Diffusion Coefficient set 200 cm²/s, uncertainty factor 2, marked with red colours spots on the Figures 7-10 in Chapter 3.

2.2.4 *Evaporation of crude oil*

Evaporation of crude oil in GNOME is not treated by the more complete theories available. GNOME uses a simplistic 3-phase evaporation algorithm (Equation 6) where the pollutant is treated as a three-component substance with independent half-lives.[4]

The pollutant type selected for the spill determines the parameters chosen for the weathering simulation and there is evaporation if the oil type requires. [3]

$$X_{prob} \frac{P_1\left(2^{\frac{-t_i}{H_1}} - 2^{\frac{t_{i-1}-2\times t_i}{H_1}}\right) + P_2\left(2^{\frac{-t_i}{H_2}} - 2^{\frac{t_{i-1}-2\times t_i}{H_2}}\right) + P_3\left(2^{\frac{-t_i}{H_3}} - 2^{\frac{t_{i-1}-2\times t_i}{H_3}}\right)}{P_1\times 2^{\frac{-t_i}{H_1}} + P_2\times 2^{\frac{-t_i}{H_2}} + P_3\times 2^{\frac{-t_i}{H_3}}} \quad (6)$$

where:
t & t_1 are the time elapsed (age; in hours) at time-step *i* & the previous time-step *i-1*, respectively;
H are the half-lives of each constituent (in hours) from Table 3 for the pollutant;
P are the percentages of each constituent (as decimals) from Table 3 for the pollutant.

Table 3. Crude oil pollution example type, their default composition, and half-lives parameters. [3]

Pollutant Type	Percent each constituent	Half-Life each Constituent [h]	Observational Threshold Time [h]
Medium	22.0	14.4	170.1
Crude Oil	26.0	48.6	170.1
	52.0	10x109	170.1

2.2.5 *Spills of crude oil*

Spilled substances are modeled as point masses (up to 10,0004) called LE's (Lagrangian elements) or "splots" (from "spill dots"). Pollutants are not treated as blobs with variable volume and thickness. Parameters assigned to each point mass include location (latitude/longitude), release time, age, pollution type, and status – floating, beached, evaporated – see Table 4.

Table 4. Information carried by each LE. [3]

Parameters	Units	Descriptions
leKey		indexed LE identity
leCustomData		space for custom LE data; currently = 0
position	[decimal degrees]	latitude, longitude position
z	[m]	depth
releaseTime		time of release in spill
age	[sec]	time since release
clockRef	[sec]	time offset
pollutantType		LE pollutant type for weathering (Table 1)
mass	[g]	amount of pollutant in LE
density	[g/cm³]	pollutant density
statusCode		code to indicate whether or not LE is released, floating, beached, etc.
bVisible		flag to indicate whether or not LE is drawn
lastWaterPt		last on-water location of LE before beaching
beachTime	time when LE was beached	

In simulation considered continuous 10 minutes crude oil release from the one-point pipeline system after pipeline rupture.

2.2.6 *Trajectories of crude oil*

Once the map, movers, and spills are set, the model is run, and the solution is produced in the form of trajectories. GNOME provides two solutions to an oil spill scenario:
– a "best estimate," or forecast, trajectory,
– a "minimum regret," or uncertainty, trajectory,

The "best estimate" solution shows the model result with all the input data assumed to be correct. However, models, observations, and forecasts are rarely perfect. Consequently, the GNOME introduced understanding of the uncertainties (such as variations in the wind or currents) that can occur.

This second solution a "minimum regret" allows the model to predict other possible trajectories that are less likely to occur, but which may have higher associated risks.

GNOME introduced the trajectory that incorporates these uncertainties the "minimum regret" solution because it gives you information about areas that could be impacted if, for example, the wind blows from a somewhat different direction than you have specified, or if the currents in the area flow somewhat faster or slower than expected. In some cases, the areas within the minimum regret solutions might be especially valuable or sensitive to oiling. [3]

Both trajectories are represented by LE's, which are statistically independent pieces of the modelled pollutant. They appear as small "pollutant particles" on a map of simulation area when spill is running. The "best guess" trajectory is represented by black "splots" (from "spill dots"); the "minimum regret" trajectory is represented by red "splots".

2.2.7 *Windage*

Windage is the movement of oil by the wind. This is typically about 3% of the wind speed based on analytical derivation and empirical observation that oil tends to spread out in the direction of the wind. [5]

Experience and observation have led us to use a factor in the range 1 - 4%, adjusted based on overflight reports.[6]

This range is used as the default in GNOME with a uniform distribution. A given oil droplet will move differently depending on how close it is to the wind effects at the surface. The windage is lower as the oil weathers and spends more time below the surface.

3 RESULTS

The results of simulation are presented below on Figures 4 - 6 without the uncertainty factor. The oil spot is moving according to wind direction slowly increasing the surface due to the diffusion. Dominant wind directions caused that the oil spot is moving towards to the land - Vistula Spit, where are located touristic places & beautiful beaches.

Figure 4. Oil spot moved due to the wind - GNOME. [2]

Figure 5. Further drift of oil spot eastward - GNOME. [2]

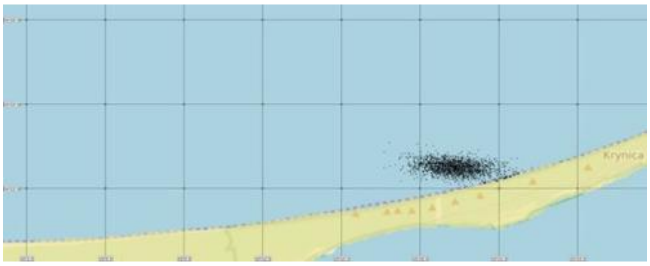

Figure 6. Oil spot drift to land - Vistula Spit - GNOME. [2]

The Figure 7 illustrated the trajectory of oil spot with 4-hour interval from the place of origin the spill - Oil Terminal to the beach located on Vistula Spit.

Figure 7. Trajectory of oil spill with interval every 4 hr - Google Earth.

Figures 8 - 11 below presented the same trajectory of oil spot with the uncertainty factor. Where the black spots mean the "best guess" trajectory and the red spots represented the "minimum regret" trajectory.

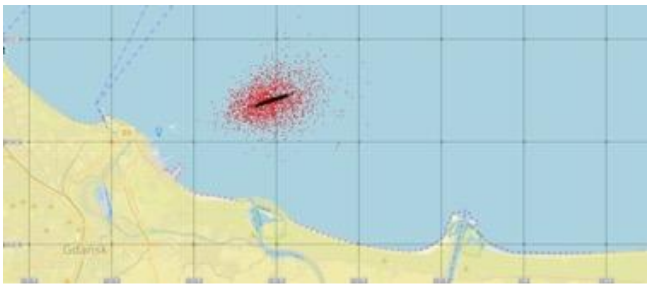

Figure 8. Oil spot moved due to the wind with uncertainty factor - GNOME. [2]

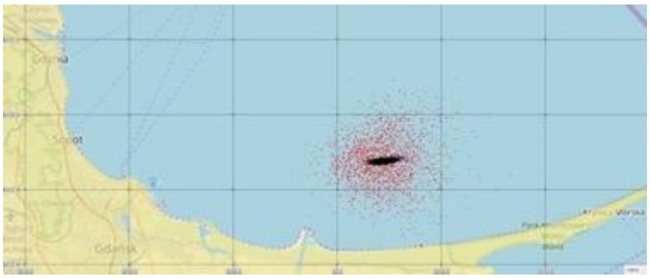

Figure 9. Oil spot moved with random walk - GNOME. [2]

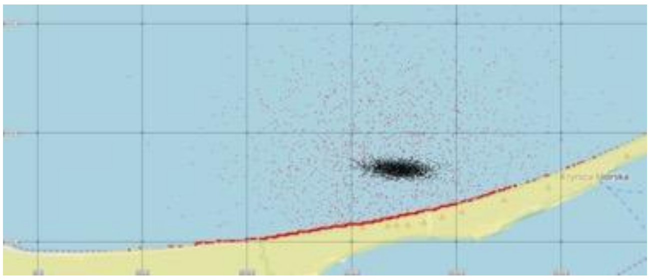

Figure 10. Oil spot with random walk - GNOME. [2]

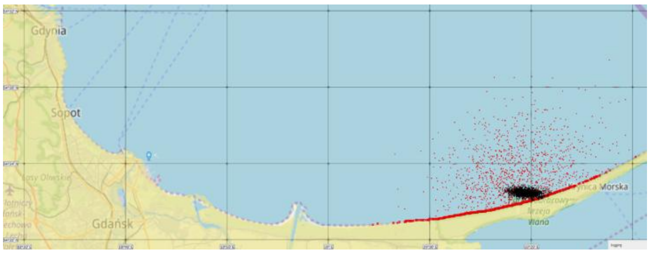

Figure 11. Oil spot ashore - GNOME. [2]

Figures 12 below contain the estimated dimensions of the pollution track without the uncertainty factor, where:

- d is diameter of pollution,
- A is area of the pollution,
- P is perimeter of the pollution,

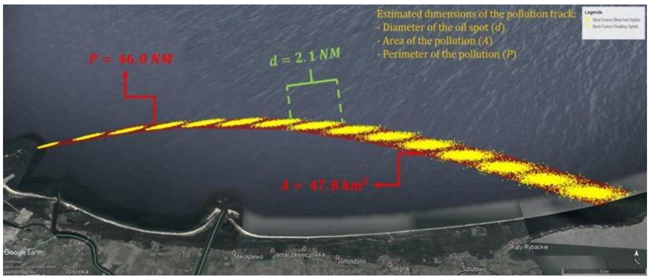

Figure 12. Estimated dimension of the oil spill trajectory without the uncertainty factor - Google Earth.

Figures 13 below presented the estimated dimensions of the pollution track including the Minimum Regret (the uncertainty factor), where:

- A is area of the pollution,
- P is perimeter of the pollution,

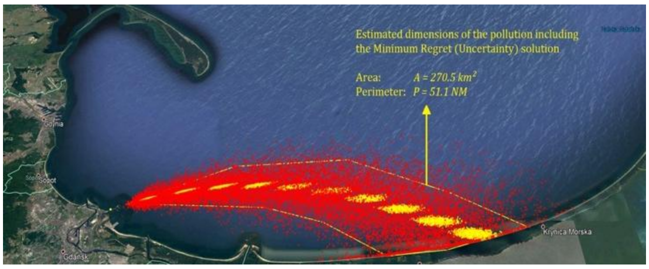

Figure 13. Estimated dimensions of the pollution including minimum regret.

4 DISCUSSION

The possibility of presenting and predicting the trajectory of a drifting oil spill on the sea surface, as well as determining its size, will allow for the proper use of emergency services to fight with oil spills.

Properly determined oil spill size requires the use of relevant methods appropriate for the hydro-meteorological conditions and the place of spillage.

Use the GNOME application allow the operators of Oil Terminal develop the most likely scenarios of events and based on them, assess the ability and readiness of emergency services to take antipollution action. [8]

In the case of insufficient forces and means to fight with oil spills, investments will be necessary to ensure the safety of the port and surrounding region.

This applies primarily to the beaches located on Vistula spit and Natura 2000 areas where oil spillage can reach. Collecting the oil residues will be laborious and costly, and the region will lose its tourist attractiveness for several years.

Successful shoreline clean-up depends on the timely availability of personnel, equipment, and materials and upon the quality of the organization established to manage and conduct the operation. Also, the type of shoreline determines the most appropriate clean-up technique to be used. [9,10]

Future research should be focused on specialized ship, equipment, and manpower especially on their capacities to combat with the amount of oil, which could be released during cargo handling in Oil Terminal or due to ship's accidents on fairway to protected environment in south part of Gdansk Bay.

Az recommendation ITOPF manpower and equipment should be identified in the local contingency plan and regularly mobilised in practical exercise to test their effectiveness. [9,10]

5 CONCLUSIONS

GNOME application is very useful multitool to predict trajectory of oil spill with all factors affecting the direction and speed of the oil spot on sea surface. It could be used to support decision making during planning and developing oil spill plans for the oil terminals. Every oil terminal should ensure that all means (ship and material) to combat with oil spill on the sea surface is sufficient and the personnel is properly trained.

Many years ago, only TRANSAS issued Oil Spill Simulator, which allow to assess the trajectory of oil spot with all assisted factors. Nowadays generally available application GNOME looks like the properly tools to make assessment during oil spillage. GNOME use many additional functions which are prepared for many locations USA together with all movers, but for other location there are many options too to apply this solution.

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