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Oil spill modelling methods: application to the south–eastern part of the Baltic Sea

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Abstract The state-of-art in oil spill modelling methods is summarized, focusing on development since 2000. Some recommendations for possible application of these methods to the south–eastern part of the Baltic Sea are prepared. Particular attention is paid on the methods of parameterization of volume of oil spill and calculation of advection of the oil spills. Consideration is also given to methods used in oil weathering models.

Keywords *• oil spill models • numerical models • review • oil weathering*

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INTRODUCTION

The anthropogenic and natural impacts on the coastal zone of the south-eastern part of the Baltic Sea are constantly increasing. One of the main sources of such influence is oil pollution, the risk of which is growing due to the rising level of oil transportation, as well as the presence of companies engaged in the extraction and transfer of oil (Ahmed 2009). Oil spills can easily destroy coastline ecosystems, marine life and require huge financial investments to combat them (Ovsiyenko *et al.* 2007; Chubarenko *et al.* 2004). In addition, the presence of many recreational areas, fisheries, national park "The Curonian Spit" in the South–Eastern Baltic region determines the relevance of timely and adequate response to possible threats. One of such instruments for solving the problem of fast response to threats is numerical modelling. Numerical modelling is widely used to limit the consequences of oil pollution, to determine their potential sources and the most vulnerable areas (Ovsiyenko *et al.* 2005; Ambjorn 2008).

The purpose of this study is to present an overview of the existing methods applied in numerical oil spill models and make some recommendations for possible application of these methods for the south–eastern part of the Baltic Sea. This paper focuses on developments since 2000. A comprehensive review of the state-of-art in oil spill modelling for earlier works was completed in Malcolm, Spaulding (1988), ASCE (1996) and Reed *et al.* (1999).

OIL SPILL MODELS IN GENERAL

Currently there are many different models describing the propagation and spreading of oil pollution on the water surface (Legrand, Duliere 2012; Lardner 2004; Berry *et al.* 2012). Even though the features of these models depend on their goal, all these models have a similar structure (Fig. 1).

Oil spill model is a complex system that includes a different numbers of sub-modules. Typically, it has three main modules: input module, transport (trajectory) module and fate (weathering) module. Input module provides information about initial conditions of the model and normally is divided into two parts: initial data about environment (wind and current field, temperature, ice, etc.) and initial data about oil spill (type, volume, properties, location and time of occurrence, etc.). Environmental data

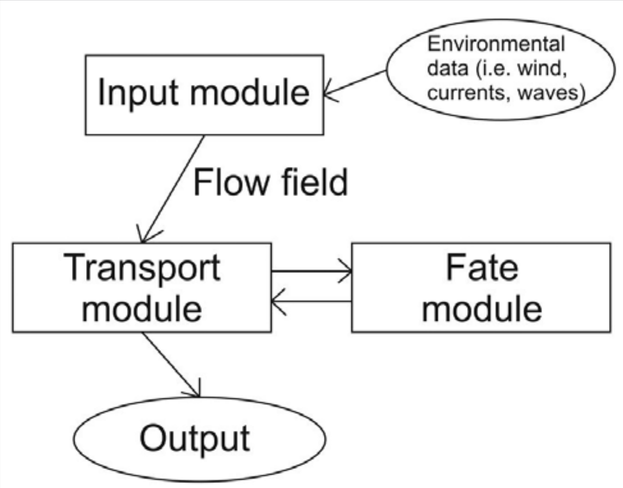

Fig. 1 General structure for oil spill models.

are mostly derived from other hydrodynamic models and, sometimes, from field observations. For example, HIROMB is an operational hydrodynamic model for the Baltic Sea developed by Swedish Meteorological and Hydrological Institute that provides information about various environmental parameters (Funkquist, Kleine 2003). The parameters of this model used as input data for oil spill models in Ambjorn (2008) and Stanovoy *et al.* (2011).

Transport and fate modules are the main part of oil spill models. They directly describe the dynamic of processes that occur with oil spills. The main task of the transport module is to provide information about advection of oil spill, using environmental forcing from input module: wind, currents and waves, while the fate module presents information about processes such as spreading, evaporation, dispersion, emulsification, biodegradation, sedimentation, etc. The number and complexity of the described processes depend on the goal, but addition of more processes and features will inevitably increase the complexity of calculations.

TRANSPORT MODULE

The main objective of the transport module is to describe the drift trajectories of the oil spill in marine environment under forcing of wind, currents and waves. Currently existing models can be divided into groups according to approach used to describe 1) oil volume in the model (particles, tracers, or spillets), 2) advection of oil spill.

Parameterization of volume of oil spill

Oil spill is a complex liquid consisting of nearly 3,000 ingredients, most of which are easily transformed by atmospheric, chemical and biological processes (Anosov, Kiper 2010). Most important characteristics are defined by its fractional composition and density. It is not easy to parameterize the oil spill considering all its properties. According to literature one can distinguish three common methods for describing the volume of oil: by particles, by tracers, and by spillets. In the particle method, a volume of oil is parameterized as a finite number of particles. Each particle is characterized by initial location and mass. Advection of each particle is calculated independently using the environmental fields (wind, currents and waves). Other processes, such as dispersion, spreading, diffusion, etc. maybe also considered. Such method is described (Guo, Wang 2009; Diaz *et al.* 2008). In Diaz *et al.* (2008), for example, every particle of oil spill is considered as inert, drifting under the wind and currents forcing, not interacting with other particles, and many processes (chemical reactions, evaporation, sinking, emulsion) are not taken into account.

In the tracer method, the area where the oil spill to be tracked is represented by passive tracer transported at the ocean's surface. This approach has been successfully used (Dembitsky *et al.* 2004; Huy, Trinh 2013; Legrand, Duliere 2012) where positive value of tracer concentration corresponds to the region of water surface with oil pollution. High values of tracer at the region indicate high concentration of the oil spill. Environmental forcing is taken into account to describe tracer movement.

The spillet method is almost identical to the particle method with the exception that the spillet has more degrees of freedom than a particle. Additional parameters of spillets can be used to describe extra properties of oil spills (for example, the area or thickness of spill). The total oil spill is described as a number of spillets. Each spillet may have its own properties and this allows to represent a complex structure of oil spill without consideration a multiphase fluid. This method is most common for modern models. It has been used in numbers of operational models all over the world (Ambjorn 2008; Lardner 2004; Berry *et al.* 2012). As an example of spillet models the oil drift model PADM (Particle Dispersion Model) developed by the Swedish Meteorological and Hydrological Institute together with the Danish Maritime Safety Administration could be mentioned (Ambjorn 2008). Each spillet of oil spill has a set of properties (the most important is a position). The spillet can also have a variety of additional properties depending on type and parameters of oil spill (e.g. mass, volume, size, chemical properties, density, etc.). These properties can be constant or dependent on time, location or temperature. Another interesting example of spillet method is described in Zelenke *et al.* (2012) and Beegle-Krause (1999). Model GNOME was developed in the Office of Response and Restoration (OR&R) of NOAA/ERD (National Oceanic Atmosphere Administration / Emergency Response Division, USA). In GNOME, the spillets are a collection of points that represent the volume of oil spills. Initial distribution of oil spill can vary in space (point, line, or sprayed distributions) and in time (point and line sources simulate instantaneous spills or spills over time). The model tracks the mass balance of the oil, as well as the uncertainty associated with the trajectories.

Calculation of advection of the oil spills

It is also possible to highlight the two main approaches: *Lagrangian* approach and approach of nonstationary diffusion equation for tracer (*Eulerian* approach). The most common and widely used method is Lagrangian approach. In this approach, the environmental characteristics are simulated as Eulerian fields within which the oil spill Lagrangian elements (particles or spilles) move. It is assumed that the particles (spillets) do not influence the flow field. This method successfully used in following operational models: GNOME (NOAA) (Zelenke *et al.* 2012), BIOCAST (NRL) (Jolliff *et al.* 2014), BOLT (Bedford Institute of Oceanography) (Nudds *et al.* 2013), PADM (SeaTrackWeb) (Ambjorn 2008), module Mike21 SA (Anonymous 2004). The positions in the flow of every single particle or spillet are calculated using environmental data (wind, currents, and waves). The model of passive advection of a Lagrangian particle in one dimension is described by the following equation (in PADM):

$$\frac{dx_P}{dt} = v(x_p(t)) \qquad (1),$$

where, $x_P(t) = (x_P(t), y_P(t), z_P(t))$ is the particle position coordinates at time *t* and $v(x_p(t))$ is the corresponding velocity vector determined by the flow field. The entire set of such equations describes the drift of the oil spill.

The approach of nonstationary diffusion equation for tracer is used (Huy, Trinh 2013; Dominicis *et al.* 2013; Cho *et al.* 2012). This method represents oil spill as concentration of passive tracer and for calculation of its transport uses nonstationary diffusion equations. In the model presented by Huy and Trinh (2013), there are two layers: surface and subsurface. Distribution of concentration of oil in the layer is uniform by thickness. Evolution of oil spill is calculated separately in each layer. This takes into account the exchange of oil between the layers and its deposition on the bottom. The oil concentration in the layer is calculated using the following diffusion equation:

$$\frac{\partial C_s}{\partial t} + u_s \frac{\partial C_s}{\partial x} + v_s \frac{\partial C_s}{\partial y} = k_1\left(\frac{\partial^2 C_s}{\partial x^2} + \frac{\partial^2 C_s}{\partial y^2}\right) -$$

$$\alpha\left(C_s - C_v\right) - \gamma C_s - C_s\left(S_d + S_e\right) + f(x,y,t) \qquad (2),$$

where, C_s is concentration of oil per unit of surface water, C_v is concentration of oil in the lower layer, u_s and v_s are velocity components, α is oil exchange ratio between layers, γ is rate of biochemical destruction of oil, S_d and S_e are evaporation and decomposition rate of oil per unit area, f is intensity of inflow of oil from the source.

This approach allows calculating not only horizontal drift of oil spills but also distribution of tracer concentration in water column. There are also hybrid models that use both Lagrangian approach and nonstationary diffusion equations at the same time (Legrand, Duliere 2012). In this case, Lagrangian approach is used for calculation of oil spill transport in horizontal direction, when diffusion equation is used for calculation of distribution of tracer concentration in water column. This hybrid method can reduce the computation time because it is not necessary to solve the diffusion equations for horizontal transport, but it gives a three-dimensional distribution of oil spill for all computational domain of the model.

Comparison of Eulerian and Lagrangian approaches was performed by Cucco *et al.* (2009) applying them for the estimation of transport time scales (TTS) in the Venice Lagoon. A 2D hydrodynamic model based on the finite element method has been used for this purpose. The TTS has been computed for the Venice Lagoon by means of both an Eulerian and a Lagrangian approaches. The obtained results have been compared in order to identify the main differences between the two methods. The Eulerian water transport time (WRT) scale has been computed through the definition of the remnant function of a passive tracer released inside the lagoon whereas the Lagrangian water transport time (WTT) scale has been computed tracking the trajectories of simulated particles released inside the basin. Numerical computations showed that the results obtained by two techniques, when applied to a tidal active coastal basin, characterized by a complex morphology and dynamic, are differently influenced by the tidal variability. In particular, the type and the phase of the tidal forcing at the beginning of the computation, strongly influence the WTTs distribution within the basin. On the other hand, the WRTs computation is not affected by the tidal forcing variability.

FATE MODULE

The fate of the oil spill is also influenced by weathering processes (i.e. evaporation, emulsification, sinking, sedimentation and biodegradation), which contribute to changes in the oil mass and properties. Two basic methods are used for weathering : 1) method based on tables of empirical data for relevant oil properties which show how these properties change in time (Daling *et al.* 1997; French McCay, Isaji 2004), and 2) approach based on simple empirical formulae (Ambjorn 2008; Cucco *et al.* 2012). The fate model SINTEF which is widely used in Europe (Ambjorn 2008) is based on tables of empirical data for oil properties, which represent the dynamics of these properties in time

(Daling *et al.* 1997). Such processes as evaporation, emulsification, density and viscosity, are calculated by interpolation.

In (Vos 2005) a detailed comparison of five pre-selected oil weathering models (ADIOS, MEMW-DREAM, GNOME, SINTEF and SIMPAR) was performed. Test results allow to state that results are very sensitive to the input parameters used in the models. Thus, the existence of a reliable oil databases is a prerequisite for use of these oil-weathering modules. According to the opinion of authors, SINTEF seems to be most reliable since its oil database is fully based on lab experiments, data source for ADIOS-2 is not known, and there is no oil data base for SIMPAR, whereas for GNOME it is limited to six oil types.

APPLICATION FOR THE SOUTH–EAST BALTIC

All models that are used in the world today require accurate and timely obtained initial parameters, because results are very sensitive to them. Thus, for adequate response to possible threats it is necessary to have high-resolution hydrodynamic and atmospheric operational models. Accurate flow field for study areas that are typically caused by wind, currents and waves data is one of the most important parts of the oil spill models.

Problem of accurate flow field for oil spill modelling was considered in Broström *et al.* (2014). In this paper authors investigate the performance of two different oil spill models: the operational oil spill model Seatrack Web (Ambjorn 2008) and OD3D (Martinsen *et al.* 1994; Wettre *et al.* 2001). The simulation of *Golden Trader* accident in September 2011 outside the Danish coast was performed by both models. Both models reproduced relatively similar evolution of the oil spill trajectories in the initial part of the trajectory modelling, but they deviate approaching the Swedish coast where higher spatial resolution is necessary.

Another problem discussed in Broström *et al.* (2014) was the problem of beaching of oil. As oil spill encounter shoreline, part of the spill may be deposited and the remaining oil continues to drift. The position where the oil beaches is an important output parameter for oil spill models. The authors noted that although the beaching is a very important parameter in oil spill models the mechanism of this process is not adequately described in the models. For example, in OD3D and BSHcmod, the oil is beached on the edge of the numerical grid but the coastline is not represented accurately enough in these models.

The south–eastern part of the Baltic Sea is composed of a number of areas with different hydro-geo-morphological regimes. They differ by features that determine the pattern of flow field. Usually classifications of such areas are based on morphological and/or hydrological parameters (Nowacki, Jarosz 1998). In Andrulewicz *et al.* (2004) division of the Gulf of Gdansk based on bathymetry and morphology was made as follows: inner coastal area (0–10 m depth), outer coastal area (10–20 m depth), and open sea area (>20 m depth). It was also mentioned that the open sea area between 20–40 m are still under coastal influence; open sea area deeper than 40 m – most of these south-east Baltic Sea water masses are not under direct coastal influence.

Thus, the description of processes close to the coast may be vital for accurate forecast of oil drift. For more accurate response and for near-shore areas it is necessary to have high-resolution hydrodynamic and atmospheric models to obtain high-resolution flow fields and, because the model will work at coastal area, it is important to consider the interaction of oil spill with shoreline.

For oil spill modelling of the south-eastern part of the Baltic Sea it is necessary to differentiate approaches that will be used at different areas. It is reasonable to divide the whole study area into three major parts: the coastal area (0–20 m depth), where the water masses are under direct coastal influence; the offshore (>20 m depth), where the water masses are not under direct coastal influence; and the lagoons.

For the south–eastern part of the Baltic Sea it is reasonable to use the oil drift forecasting system – Seatrack Web (STW) (Ambjorn 2008), which was developed by Swedish Meteorological and Hydrological Institute. Data of meteorological model HIRLAM and hydrodynamic model HIROMB are used as input parameters for this model. STW uses the oil drift model PADM (Particle Dispersion Model) based on Lagrangian particle tracking method. The STW model calculates the transformation of various oil spills for the next 48 hours with a spatial resolution of three miles. The forecast updates every three hours as wind and current fields forecast changes. SeaTrack Web allows to solve wide range of different problems, such as detecting a potential sources of oil spills, prediction of drifting and fate of oil spills, etc. It has web interface, is operational 24 hours per day and is user friendly. The graphical user interface developed by SMHI and based on open source GIS-server technology. All these features of Seatrack Web makes it very useful tool for rapid response to oil pollutions in the south–eastern part of the Baltic Sea. However, the low spatial resolution does not allow using the model for accurate response for coastal area of the south–eastern part of the Baltic Sea. Seatrack Web does not account for small scale near shore oceanographic processes, i.e. there is a problem about details on the location and strength of eddies and the dynamics in near shore areas (Broström *et al.* 2014). Seatrack Web also does not provide accurate enough information about flow fields for lagoons.

For more accurate response in coastal areas, it is necessary to have high-resolution hydrodynamic and atmospheric models to obtain high-resolution flow fields. One of the possible ways was proposed in Stanovoy *et al.* (2011) for the Gulf of Finland. Using boundary and initial conditions from models HIRLAM and HIROMB, they developed a regional three-dimensional model of the Gulf of Finland (GOFM).

Another example of regional modelling in the Baltic Sea is the Computer Aided Rescue and Oil Combating System (CAROCS), which was developed by the Maritime Institute in Gdańsk (Gajewski 1997). This is complex 3D modelling system for prediction of oil spill, including several processes (i.e. advection due to currents and winds, horizontal and vertical diffusion of oil particles, evaporation and decomposition). This system also uses model HIROMB data as input. In Łubniewski *et al.* (2006) the web-based GIS for visualization and monitoring of marine pollutant aggregations as the sample application of the real-time, remotely accessible marine GIS was presented. This system can work with different types of data (i.e. direct sampling, satellite remote sensing and numerical modelling data), and may be applied as a useful tool for fast response to threats.

In Zemlys *et al.* (2013), the results of testing an operational hydrodynamic model HIROMB_LT for Lithuania's coastal zone are presented. Using a HIROMB model for the Baltic Sea (Funkquist, Kleine 2003, 2007) the regional model was developed. The main advantage of this model was a high-resolution model grid with horizontal resolution 300 m and vertical resolution 25 layers. HIROMB_LT model covers the Baltic Sea coastal area reaching the Gdansk Bay in the West and Latvian border in the North and the Curonian Lagoon. Authors conclude that the local model performs considerably more adequately than the global HIROMB model for the whole Baltic Sea with 1 nm horizontal resolution. It is obvious that Seatrack Web currently used in the south–eastern part of the Baltic Sea and based on HIROMB hydrodynamics simulated with 3 nm resolution is unable to resolve oil drift for this coastal area properly and development of the regional high resolution model is reasonable.

For the lagoons of the south–eastern part of the Baltic Sea, a special approach should be applied. Lagoon has specific conditions of hydrological regime, relief formation and sedimentation (Brovko 1990). Thus, for these regions the additional high-resolution models should be developed. For the modelling of hydrodynamic conditions in the lagoons and water exchange with the adjacent sea area it's recommended to use a software package such as SHYFEM, developed at the Institute of Marine Sciences, National Research Council of Italy, ISMAR-CNR, Venice, Italy. It was repeatedly applied to the Mediterranean lagoons (Umgiesser *et al.* 2014). This software package is developed for both tidal and tide-free lagoons, has the ability to accounts deep channels together with the shallow water areas, allows to change the code, so it is suitable enough to use for modelling situations in the lagoons of the south–eastern part of the Baltic Sea.

It is recommended also for lagoons to use software package MIKE (MIKE Flow Model) (DHI Water & Environment)**,** a professional engineering software package containing a comprehensive modelling system for 2D free-surface flows and 3D flows, applicable to the simulation of hydraulic and related phenomena in lakes, estuaries, bays, coastal areas and seas where stratification can be neglected. The hydrodynamic module is the basic module in the MIKE Flow Model. It provides the hydrodynamic basis for the computations performed in the Environmental Hydraulics modules. This software package already has oil spill module – Mike21 SA and already was applied for the basins (Vethamony *et al.* 2007).

CONCLUSIONS

Numerical modelling is one of the instruments to support the fast response to threats. There are various models being used to predict the drift and dispersion of oil. These models are based on different methods. Currently existing models can be divided into groups according to approach used to describe 1) oil volume in the model (particles, tracers, or spillets), 2) advection of oil spill. Three common methods for describing of volume of oil can be distinguished: particles, tracers, and spillets. Two main approaches for calculation of advection of the oil spills are used in the models: Lagrangian approach and approach of nonstationary diffusion equation for tracer (Eulerian approach).

All models used in the world today require accurate and timely obtained input parameters, because results are very sensitive to them. Accurate flow fields that are typically based on wind, currents and waves data, is one of the most important prerequisite for the oil spill models. Thus, for adequate response to possible threats it is necessary to have high-resolution hydrodynamic and atmospheric operational models.

The following recommendations should be followed by implementation of oil drift models in the south–eastern part of the Baltic Sea:

- to divide the region into three major areas: coastal area of the south–eastern part of the Baltic Sea (0–20 m depth), where the water masses are under direct coastal influence; the offshore of the south-eastern part of the Baltic Sea (>20 m depth), where the water masses are not under direct coastal influence; and lagoons;

- for the oil spill in the south-eastern part of the Baltic Sea (>20 m depth), it is recommended to use the oil drift forecasting system Seatrack Web (Ambjorn 2008);
- for the oil spill in the coastal area of the south-eastern part of the Baltic Sea (0–20 m depth), it is recommended to develop a regional model based on operational data from models HIRLAM and HIROMB. Lagrangian method is recommended to use for transport module. As the fate module the SINTEF is recommended to be use;
- for the oil spill in the lagoons of the south–eastern part of the Baltic Sea it is recommended to develop additional high-resolution models, using the software package SHYFEM (Umgiesser *et al.* 2014) or MIKE Flow Model (Anonymous 2004);
- it is recommended to perform differentiation of the coasts for the oil retention capacity. This differentiation should be used as a boundary condition in the regional model for more accurate accounting of oil-coast interaction processes.

Implementation of recommendations can significantly improve quality of oil spill modelling for the south–eastern part of the Baltic Sea. Development of a high-resolution regional oil spill model will allow obtaining of high-resolution flow fields for study area that will help to simulate oil spill drift more accurately.

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