RISK ASSESSMENT OF OIL SPILL ACCIDENTS
PART 1: PRESENTATION OF THE METHODOLOGY

A.I. STAMOU¹, E. N. OTAY², V.K. TSOUKALA¹, N. COPTY², F.T. KARAKOC³, G. CHRISTODOULOU¹, A. PAPADOPOULOS⁴, G. PAPADONIKOLAKI¹ and Y.C. ALTAN²

¹School of Civil Engineering, Water Resources and Environmental Engineering, National Technical University of Athens, Iroon Polytechniou 5, 15780 Athens, Greece. e-mail: stamou@central.ntua.gr
²Boğaziçi University, 34342, Bebek, Istanbul, Turkey. e-mail: otay@boun.edu.tr
³Tübitak Marmara Research Center, Gebze, Kocaeli, Turkey. e-mail: fatma.tellikarakoc@tubitak.gov.tr
⁴Institute of Inland Waters, Hellenic Centre for Marine Research, 46.7 km Athens-Sounion Avenue, 19013, Anavyssos, Attiki, Greece. e-mail: tpapa@hcmr.gr

EXTENDED ABSTRACT

Oil slicks often occur due to sea casualties and have severe environmental and ecological impacts on sea and coastal ecosystems. When the oil is leaked into the seawater it spreads forming a spill and a series of physical, chemical and biological processes take place (weathering processes), such as transport, dispersion, dissolution, evaporation, emulsification, sedimentation and biodegradation. Various mathematical models have been developed in order to describe this behavior and predict the oil spill trajectory and impacts after a sea accident for operational actions to avoid or mitigate the pollution impacts.

The objective of this study is to develop an integrated stochastic approach for quantifying the risk of oil spill in marine waters. The proposed methodology that can be applied in a particular marine region integrates (1) a physics-based hydrodynamic model, (2) an oil spill transport model, (3) an accident assessment model that computes the probability of oil accident at a particular region of the sea, and (4) an expert-based risk assessment model to compute the spatial distribution of the oil spill risk. In the present paper the applied integrated modelling methodology is presented with special reference on the linking of the different models. This objective was achieved via the effective cooperation of the researchers of the National Technical University of Athens (NTUA) and the Bogazici University (BU) within the frame of a joint research project; the research team of the NTUA developed the hydrodynamic and the oil slick model, while the BU researchers developed the accident assessment model and the risk assessment model. The stochastic nature of the proposed methodology provides a better and a more reliable procedure for the calculation of the oil spill risk in marine waters; subsequently, the threat of oil spill on the environment is expected to be reduced. The proposed methodology is expected to help the partner countries to improve their readiness to potential oil spill hazards.

Keywords: Oil slick; sea accidents; oil pollution; oil weathering; hydrodynamic model; oil spill model; risk assessment model.

1. INTRODUCTION

Oil spills into coastal waters and open seas have the potential to cause significant adverse impact on marine environments, such as the Exxon Valdez oil spill in 1989 that
released more than 40,000 tons of crude oil in Alaska. Subsequently, in the last decades studies have been performed aiming at understanding and addressing the ecological, navigational and legal problems resulting from oil spill accidents. A significant number of these studies have been concentrated in the development of mathematical models to describe the physical, chemical and biological processes that control the fate and transport of oil spills in surface waters (e.g., Mackay, 1980; Huang and Monastero, 1982; ASCE Task Committee, 1996; Wang et al., 2005, 2008; Zadeh and Hejazi, 2012), which commonly are advection turbulence, evaporation, dissolution, emulsification, biodegradation, vertical dispersion and sedimentation. Generally, these models are used to enhance oil spill preparedness and to develop contingency planning that sometimes direct the response operations.

Given the complexity of the factors influencing the governing mechanisms some researchers have attempted to formulate the oil spill problem within a stochastic framework that accounts for uncertainty in the definition of some of the input parameters (Al-Rabeh et al., 1989; Reed and Gundlach, 1989; Guo and Wang, 2009). The goal of such models was primarily to identify the shorelines that are at highest risks from oil spills and estimate the time needed for the spilled oil to reach these shorelines. Another group of researchers have attempted to develop models that can predict the chance of accidents; for example, oil tanker collisions or grounding, from human factors and environmental conditions that include weather and hydrodynamic conditions, navigation hazards, traffic and vessel characteristics. These attempts, however, are very rarely used in conjunction with physics-based hydrodynamics and oil transport models to evaluate shoreline risks. In one of the first attempts in that direction, Tan and Otay (1999) described a physics-based mathematical model to predict the maritime accident risk in narrow waterways using a stochastic theory. However, the problem for larger seawater bodies remains unanswered; only a few efforts have been made in the years followed, where operations research articles were published proposing complex mathematical tools based on neural networks or fuzzy logic, which have mainly ignored the undisputable effects of physical forces and the random nature of environmental forces which control both the accident and the fate of oil.

With increasing involvement of practitioners in the problem, some countries have started to develop national oil spill preparedness plans by applying statistical tools to their coastal waters (SafeTec, 1999; BMT, 2004; MRC, 2010); these plans have implemented simple decision tools that are mainly based on expert judgment to develop large scale oil spill risk maps. From the practical point of view, these maps proved themselves to be useful; however, they lack a scientifically proven relationship between the cause of an oil accident and the impact of the spill.

The purpose of this study is to develop an integrated stochastic approach for quantifying the risk of oil spill in marine waters. The proposed methodology that can be applied in a particular marine region integrates (1) a physics-based hydrodynamic model, (2) an oil spill transport model, (3) an accident assessment model that computes the probability of oil accident at a particular region of the sea, and (4) an expert-based risk assessment model to compute the spatial distribution of the oil spill risk. In this paper the applied integrated modelling methodology is presented with special reference on the linking of the above-described models. The application of the proposed methodology into two case studies is presented in Stamou et al. (2013).

2. OVERVIEW OF THE METHODOLOGY
The main objective of this study, which is to develop a methodology that quantifies the risk of oil spills in marine waters, was achieved via the effective cooperation of the researchers of the National Technical University of Athens (NTUA) and the Bogazici
University (BU) within the frame of a joint research project; see acknowledgement. The methodology that was developed by the joined efforts of the researchers of the two Universities is shown schematically in Figure 1 and is described in the following sections. Very briefly, the research team of the NTUA developed the hydrodynamic and the oil slick model, while the BU researchers developed the accident assessment model and the risk assessment model. A simple version of the proposed methodology was applied in Saronicos Gulf and the Gulf of Izmir; these applications are presented in Stamou et al. (2013).

Figure 1. Schematic presentation of the proposed methodology.

3. HYDRODYNAMIC MODEL
The hydrodynamic model FLOW-3DL (Stamou et al., 1999; 2007a; 2007b) involves the 3D non-steady state shallow water, continuity and momentum equations, expressed in layer formulation. Using fixed permeable interfaces between layers, the equations of the model are vertically integrated. The following assumptions are made: (i) the distribution of the pressure (p) is hydrostatic, (ii) the Boussinesq approximation is valid, and (iii) p at the surface is set equal to the atmospheric (zero). The continuity and momentum equations of the model read as follows:

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + W \frac{\partial U}{\partial z} = fV - \frac{1}{\rho} \frac{\partial P}{\partial x} + \frac{\partial}{\partial y} \left( v_h \frac{\partial U}{\partial x} \right) + \frac{\partial}{\partial z} \left( v_v \frac{\partial U}{\partial z} \right)$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + W \frac{\partial V}{\partial z} = -fU - \frac{1}{\rho} \frac{\partial P}{\partial y} + \frac{\partial}{\partial x} \left( v_h \frac{\partial V}{\partial x} \right) + \frac{\partial}{\partial z} \left( v_v \frac{\partial V}{\partial z} \right)$$

$$\frac{\partial P}{\partial z} = -\rho g$$

The variables of the equations are the layer-averaged velocity components $U$, $V$ and $W$, along axes $x$, $y$ and $z$, respectively, of a Cartesian coordinate system, the free surface elevation $\zeta$ and pressure $P$. Axis $z$ is taken as positive upward from the sea surface, $f$ is
the Coriolis parameter, g is the gravitational acceleration, and \( \rho \) is the water density. In the second-order diffusion terms of the momentum equations, \( v_h \) and \( v_v \) are the horizontal and vertical eddy viscosity coefficients, respectively; in this case their distributions are set constant, equal to 100 and 0.1 \( \text{m}^2 \text{s}^{-1} \), respectively. Equations (1) to (4) are solved explicitly in a staggered orthogonal grid (U, V and W are determined at the faces of the control volumes, while \( \zeta \) is determined at their centers) using the upwind scheme for the discretisation of the transport terms and the central differencing scheme for the diffusion terms. The boundary conditions for U, V, W and \( \zeta \) include (a) land boundaries, where the no-slip condition for horizontal velocity is applied, and (b) open sea boundaries, where the radiation condition is used for velocities (Krestenitis, 1987). The calculation procedure is as follows: firstly, the pressure distribution is determined from equation (4); then, velocities U and V are calculated by equations (2) and (3), respectively. Finally, velocities W are determined by solving the continuity equation (1), whereas the free surface elevation is deduced by equation (5) that is the linearized kinematic boundary condition at the surface layer; subscript \( \zeta \) denotes values at the surface layer:

\[
\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}U_{\zeta} + \frac{\partial}{\partial y}V_{\zeta} = W_{\zeta}
\]  

In the present work the model is applied in a single layer to compute depth averaged velocities; then, the horizontal surface current velocities in the x and y directions (\( U_{\text{surf}} \) and \( V_{\text{surf}} \)) are calculated by equations (6) and (7), according to Koutitas (1985):

\[
U_{\text{surf}} = 1.5 U + 0.03 U_{wx}
\]

\[
V_{\text{surf}} = 1.5 V + 0.03 U_{wy}
\]

where \( U_{wx} \) and \( U_{wy} \) are the wind velocity components (m s\(^{-1}\)), in the x and y directions, respectively.

4. ACCIDENT FREQUENCY AND LOCATION MODEL

The accident model predicts the frequency of marine traffic accidents and the geographic distribution of their locations; this prediction is based on the following parameters: (i) AIS (Automated Identification System) data, (ii) marine traffic data, (iii) vessel characteristics (size, type and cargo), (iv) coastal facilities, (v) statistics of occurred accidents, (vi) hydrographic data (geometry and bathymetry of the area of study), (vii) wind characteristics (speed and direction) and (viii) velocity components of the surface currents (\( U_{\text{surf}} \) and \( V_{\text{surf}} \)).

5. OIL SPILL MODEL

In the present version of the oil slick model the processes of spreading, evaporation, dissolution and emulsification are taken into account. The necessary inputs for the model are (i) the quantity (mass and volume) and the properties of the spilled oil, (ii) the velocity components of the surface currents, (iii) wind characteristics, (iv) sea characteristics (density and temperature), and (v) the locations of the sea accidents that are determined by the accident model. The particle tracking method was employed to model the advection-dispersion processes, whereas classical empirical models are applied to simulate the weathering processes. As soon as oil is spilled, horizontal spreading over the sea surface occurs, governed by gravity, momentum, surface tension and viscous forces. According to Lehr et al. (1984) the spreading, which is influenced by the wind and is non-symmetrical resembling an ellipse, can be described by equation (8):
where $A_s$ is the slick area ($m^2$); $l_{\text{max}}$ and $l_{\text{min}}$ are the lengths of the minor and major axes of the spill (m), respectively; $\Delta \rho = \rho_w - \rho_{\text{oil}}$, where $\rho_w$ and $\rho_{\text{oil}}$ are the densities of water and oil, respectively (kg $m^{-3}$); $V_o$ is the volume of the spilled oil (barrels); $U_w$ is the wind speed (knots); $t$ is time (min). Evaporation primarily determines the fate of an oil slick since it causes a rapid reduction to the volume of the spilled oil and affects the viscosity and density of the oil residue by increasing them. Mackay (1980) proposed an analytical method to compute the rate of oil evaporation, expressed by equation (10):

$$F_e = \left( \frac{T - T_o}{B T_G} \right) \ln \left( \frac{B T_G}{T} \right) \exp \left( A - \frac{B T_G}{T} \right) + 1$$

where $F_e$ is the volume fraction of the oil evaporated; $T$ is environmental temperature (K); $T_o$, $T_G$, $A$, and $B$ are constants that derive from distillation data; $T_o$ is the initial boiling point at $F_e=0$ (K); $T_G$ is the gradient of the distillation curve (K); $T$ is the environmental temperature (K); $\theta$ is the evaporation exposure, i.e. the volume of the exposed vapor at time $t$ versus the initial spill volume, and is calculated by equation (11):

$$\theta = \frac{K_2 A_s t}{V_o}$$

where $V_o$ is the initial volume of the oil spill ($m^3$); $K_2$ is the mass transfer coefficient for evaporation ($m s^{-1}$), defined by equation (12) (MacKay and Matsugu, 1973):

$$K_2 = 0.0107 U_w^{0.78} D_s^{-0.11} S_c^{-0.67}$$

where $U_w$ is the wind speed ($m s^{-1}$); $D_s$ is the oil slick diameter (m); $S_c$ is the Schmidt number which represents the surface roughness. Mackay (1980) developed a multi-component theory for the calculation of the rate of oil dissolution:

$$S_d = K_d A_s S$$

where $S_d$ is the total dissolution rate of the oil slick ($gr s^{-1}$); $K_d$ is the dissolution mass transfer coefficient; $S$ is the oil solubility in water which is given by equation (14):

$$S = S_o e^{-\alpha t}$$

where $S_o$ is the solubility of fresh crude oil ($gr s^{-1}$), $\alpha$ is a decay constant (days$^{-1}$).

Emulsification is the main weathering process that contributes to the increase of the oil volume and thus the persistence of the slick. The water droplets are dispersed into the oil mass forming a mousse of increased viscosity and density. Mackay (1980) proposed equation (15) to calculate the rate of water-in-oil emulsification which takes into account the influence of wind conditions, temperature and oil characteristics on the process:
\[ F_w = K_b \left( 1 - \exp \left( -K_a \left( U_w + 1 \right)^2 t \right) \right) \]  

(15)

where \( F_w \) is the fractional water content; \( K_a \) is a curve fitting constant that varies with wind speed; \( K_b \) is the mousse viscosity constant. According to Guo and Wang (2009), the volume and density of the oil spill increases with time due to the interacting processes of dissolution, evaporation and emulsification and is specified by equations (16) and (17) respectively:

\[ V_{oil} = \frac{V_o \left( 1 - (F_o + F_e) \right)}{1 - F_w} \]  

(16)

\[ \rho_{oil} = \rho_w F_w + (1 - F_w) \left( \rho_o + K_b F_e \right) \]  

(17)

where \( V_o \) is the initial volume of the spilled oil (m\(^3\)), \( \rho_{oil} \) is the density of the remaining oil and \( \rho_o \) is the initial density of the spilled oil (kg m\(^{-3}\)). The volume of the oil spill \( V_{oil} \), the oil density \( \rho_{oil} \) and the new mass, \( M_{oil} = V_{oil} \cdot \rho_{oil} \), are calculated in each time step using the empirical equations (16) and (17). To simulate the advection and turbulent dispersive transport of the oil slick, the particle tracking method is employed. In each time-step, the new mass of the oil slick is divided into a number of particles where the random walk procedure is employed to simulate their trajectories due to advection and dispersion. The displacement of each particle in the \( x \) and \( y \) directions is calculated, in each time-step:

\[ DS_x = U_{surf} \cdot Dt + DS \cdot \cos \theta \quad \text{and} \quad DS_y = V_{surf} \cdot Dt + DS \cdot \sin \theta \]  

(18)

where \( DS \) is the distance (m) that each particle travels due to horizontal dispersion in each time-step and is given by equation (19) (Chao et al., 2001):

\[ DS = [R]_0 \sqrt{12D_h \cdot Dt} \]  

(19)

where \( D_h \) is the horizontal dispersion coefficient (m\(^2\) s\(^{-1}\)), \([R]_0\) is a random number in the interval [0,1] to include the stochastic factor and \( \theta \) is an angle (rad) that denotes the randomness of the direction of each particle, in each time-step, due to dispersion, calculated by equation (20):

\[ \theta = 2\pi [R]_0 \]  

(20)

The new position \((X, Y)\) of each particle is calculated next, in each time-step:

\[ X = X^0 + DS_x \quad \text{and} \quad Y = Y^0 + DS_y \]  

(21)

where \( X^0, Y^0 \) are the coordinates of a particle’s position in the current time level. The total number of particles \( N \) and the oil mass \( M \) in each cell of the numerical grid can then be derived at every time-step.

6. RISK ASSESSMENT MODEL

The International Maritime Organization (IMO, 1997) defines the maritime risk as a product of accident frequency and the accident impact; therefore, the combined probability of the two conditional events of the accident at a given location and its impact is described as a combined accident risk by equation (22):
ACCIDENT RISK = [ACCIDENT PROBABILITY] x [ACCIDENT IMPACT]

The risk analysis sought to determine relative risk between different geographic locations, incident types and classes of vessel. The analysis did not consider existing controls, though these were factored in during the risk treatment process. The accident impact is determined by analysing the sensitivity parameters that include (i) Special Industrial Areas (marine fisheries areas, closed fishing areas, fishermen ports and shelters, touristic and recreational facilities, refineries, power plants, underwater power lines, factories, shipyards, cargo and passengers ports, marinas and slipways), and (ii) Special Natural Areas (coastal natural gardens, protected areas, cultural areas, important habitat areas, sea meadow, important sea mammal and bird areas).

7. DISCUSSION AND CONCLUSIONS
The stochastic nature of the proposed methodology provides a better and a more reliable procedure for the calculation of the oil spill risk in marine waters. Subsequently, the threat of oil spill on the environment is expected to be reduced; this threat refers not only to the flora and the fauna in marine waters, but also to the public life including the cultural, recreational and economic facilities along the coasts of the partner countries, such as ports, harbours, fish farms, ecologically sensitive areas, public or private beaches, hotels, historic sites and other. The proposed methodology is expected to help the partner countries to improve their readiness to potential oil spill hazards. Law makers, public administrators, and municipal planners are going to benefit from the risk assessment results by taking more effective measures to prevent and/or remediate future oil spills. One of these measures is the creation of Early Response Centres, whose locations can be optimised. Oil industry may also benefit from the reduced risk for their operations in the regional seas; moreover, oil companies, insurance companies and tanker owners may also benefit since their operational costs will be reduced.

ACKNOWLEDGEMENT
The present work was performed within the Joint Research Project entitled "Risk Assessment of Oil Spill Accidents in Regional Waters" between the National Technical University of Athens and the Bogazici University; sponsored by the General Secretariat of Research and Technology and the Turkish National Science Foundation (TUBITAK).

REFERENCES


