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RISK ASSESSMENT OF OIL SPILL ACCIDENTS

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ABSTRACT

The objective of this study is to present an integrated stochastic approach for quantifying the risk of oil spill in marine waters and adjacent coasts. This was achieved via the effective cooperation between the National Technical University of Athens (NTUA) and the Bogazici University (BU) within the framework of a bilateral joint research project. The proposed methodology integrates four models: (1) a physics-based hydrodynamic model (HYM) which computes the spatial distribution of surface water currents as the main driving force for oil transport, (2) an expert-based accident assessment model (AAM) to compute the frequency, location and characteristics of expected oil spills, (3) a physics-based oil spill model (OSM) which computes the propagation and fate of the oil slick, and (4) an expert-based impact assessment model (IAM) to compute the distribution of coastal impact due to oil contamination. The model is applied to two pilot areas: the Saronicos Gulf, Greece and Izmir Bay, Turkey. The flow fields in these areas were determined by the HYM for a large number of wind scenarios, based on which the transport and weathering of an oil slick were computed by the OSM. The most probable oil spill locations were identified by AAM based on the bathymetry, the maritime traffic and the currents. Finally, the IAM was applied to draw Coastal Oil Impact Maps in the regions of interest. Emphasis was placed on the presentation of the risk of oil reaching the coastline. Environmental sensitivity and economic importance were taken into account by assigning index values to all coastal cells.

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

1. Introduction

Oil spills due to ship accidents often occur in coastal waters and can have significant adverse impact on the marine environment. Coastal seas are at bigger oil spill risk than open oceans not only because of higher accident probability, but also due to the increased impact and sensitivity. One of the most well-known coastal oil spills of all times is the Exxon Valdez accident in Alaska with 40,000 tons, ranking 35th in the world, whereas the Atlantic Empress, the world's largest spill with 287,000 tons in the West Indies occurred almost unnoticed in open sea. The proximity to the coast alone cannot, by itself, explain the perception and the impact of oil spills. The Irenes Serenade spill (100,000 tons) in Navarino Bay, Greece, and the Independenta spill (94,000 tons) in the Strait of Istanbul, Turkey, ranked within the top 12 in the world. Yet, while the Alaska spill initiated environmental research and legislative changes in the world, the Ionian and Aegean waters are still unprotected against a disaster.

In the last decades several 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 focused on 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, such as advection, diffusion, dispersion, dissolution, evaporation, emulsification, sedimentation and biodegradation (e.g., Mackay, 1980; Huang and Monastero, 1982; ASCE Task Committee, 1996; Wang *et al.*, 2005, 2008; Zadeh and Hejazi, 2012). 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 *et al*, 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 probability of accidents due to a combination of factors, such as oil tanker collisions or grounding, 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. 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, although some complex mathematical tools have been proposed based on neural networks or fuzzy logic but ignoring the undisputable effects of physical forces and the random nature of environmental forces which control both the accident and the fate of oil. 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 based on expert judgment to develop large scale oil spill risk maps. Despite the usefulness of such maps, 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. This was achieved via the effective cooperation of the researchers of the National Technical University of Athens (NTUA) and the Bogazici University (BU) within the framework of a joint research project. The proposed methodology integrates (1) a physics-based hydrodynamic model, (2) an oil spill transport model, (3) an accident frequency 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. First, the methodology is presented with special reference to the linking of the above-described models; it is then applied to two case studies in coastal areas of the Aegean Sea, which is known for its busy maritime traffic with navigation hazards, maneuver constraints and economically and ecologically sensitive coasts. Saronicos Gulf and Izmir Bay are selected as pilot sites to assess the maritime accident and oil pollution risk for the adjacent coasts. The main criteria for case selection were the heavy ship traffic in both areas and the fact that large metropolitan areas of respective countries are located in these bays. The results are indicative, since emphasis is placed on the concept and implementation of model coupling rather than achieving quantitavely accurate results.

2. Methodology

The overall framework of the methodology is shown schematically in Figure 1 and is described briefly in the following sections. More details are given by Stamou *et al.*, (2013) and Otay *et al.*, (2013). First, a hydrodynamic model (HYM) is employed to compute the flow field and yield the surface currents for various wind scenarios. The surface currents as well as the marine traffic and vessel characteristics and wind data are taken into account by the accident frequency model to determine the probable accident locations and the respective frequencies. The most probable locations are then considered as oil spill sources for the oil spill model (OSM) which computes the respective oil slick transport taking into account the physical, chemical and biological processes involved. Finally the cumulative effect of the set of oil spills considered on each coastal segment is evaluated through the risk assessment model taking into account the sensitivity of the area and the severity of potential impact. The research team of the NTUA developed the hydrodynamic and the oil spill model, while the BU researchers developed the accident frequency model and the risk assessment model.

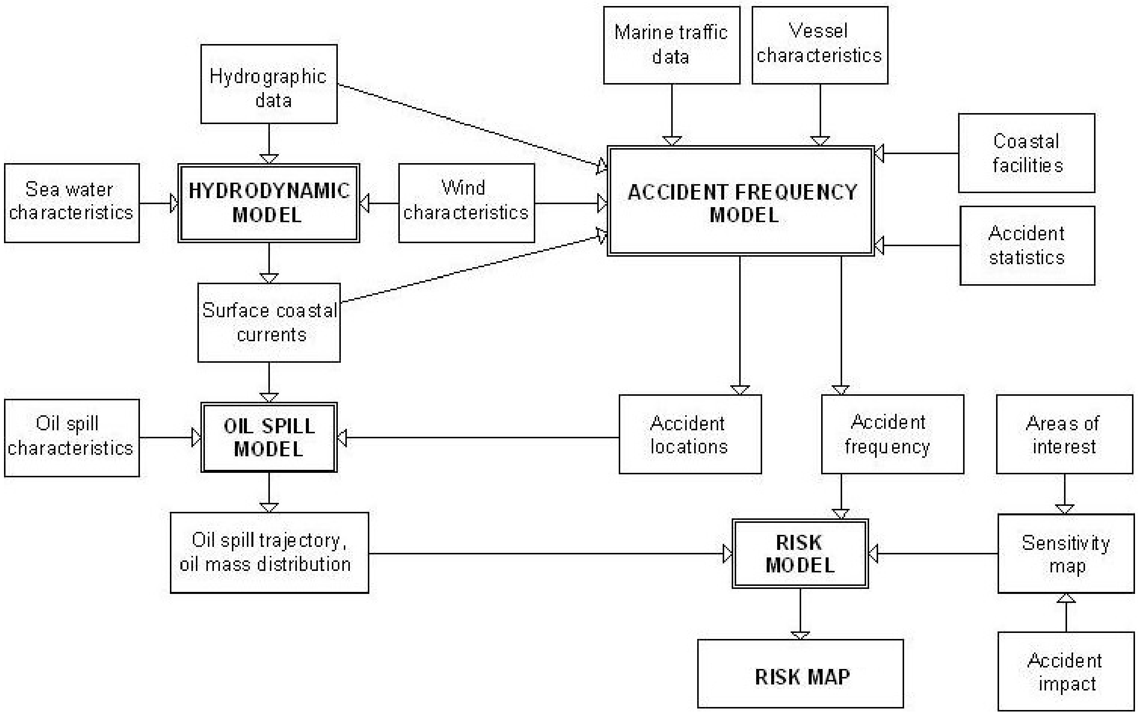

Figure 1. Schematic presentation of the proposed methodology.

2.1 Hydrodynamic model

For the description of the flow field, the hydrodynamic model FLOW-3DL (Stamou *et al.*, 1999; 2007) was employed. The model solves the 3D non-steady state shallow water (continuity and momentum) equations expressed in layer formulation, assuming hydrostatic pressure distribution and the validity of the Boussinesq approximation. The equations are solved explicitly in a staggered orthogonal grid for the layer-average velocities using the upwind scheme for the discretization of the transport terms and the central differencing scheme for the diffusion terms, taking into account the appropriate boundary conditions (no-slip on land boundaries, radiation condition on open boundaries). In the present work the model is applied in a single layer to compute the depth averaged velocities (U,V). Given this simplification, wave effects, notably Stoke's drift, are not explicitly taken into account. However, the increased horizontal surface current velocities in the x and y directions (U_{surf} and V_{surf} respectively) are calculated as follows according to Koutitas, (1985):

$$U_{surf} = 1.5\,U + 0.03\,U_{wx} \quad (1)$$

$$V_{surf} = 1.5\,V + 0.03\,V_{wx} \quad (2)$$

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

2.2. Accident frequency model

In the present model, a Bayesian network approach is adopted to calculate the relative risk in geographic segments over the entire domain (Uluscu *et al.*, 2009). Meteorological records of the study region are analyzed to determine the probability distribution of wind, which is the primary driving force of water currents. The joint probability mass functions of wind speed and direction are calculated to establish a forcing matrix of eight geographic sectors {N, NE, E, SE, S, SW, W, NW} and six wind categories given in Beaufort (bf) {1 to 6+}. Including the calm condition, the probabilities of 49 scenarios are specified and used as input conditions in the hydrodynamic model.

The resulting spatial distribution of surface currents from the 49 scenario runs of HYM are then used together with the hydrographic and navigational factors, depicted in Table 1, that are most affecting the accident frequencies in the model domain. The expert-based factors are determined by MRC (2010) for the Turkish coastal waters. As an example, the factor based on the current magnitude is selected as the probability that the surface current in a particular cell exceeds the critical velocity (V_{cr}), which is equivalent to moderate breeze (Beaufort scale 4) and is the threshold for the current to start impacting the navigation of the vessel. The other cell factors relate to the depth of water, the location of the cell relative to the coast and ship density. The relative accident frequency index for any cell is determined by summing up the relative indices for each characteristic of that particular cell. The relative frequencies are then normalized to calculate the accident frequency distribution on a scale of six for the entire domain. From this distribution, the most probable accident locations in the study area are identified, and used as initial spill locations in the OSM scenarios.

Table 1. Factors affecting accident frequency

		Relative Index							
Cell Characteristic		1	2	3	4	5	6	7	8
Current magnitude	Prob ($V>V_{cr}$)	0.00-0.06	0.06-0.19	0.19-0.31	0.31-0.44	0.44-0.50	0.50-0.69	0.69-0.81	0.81-1.00
Ratio of shoals (depth<5m) to total area	$A_{<5m}/A_{tot}$	0	0.00-0.15	0.15-0.30	0.30-0.45	0.45-0.60	0.60-0.75	0.75-0.90	0.90-1.00
Distance offshore	km	>20	15-20	10-15	5-10	0-5			
Maneuver restriction index	No. of adjacent dry cells	1	2	3	4	5	6	7	8
Ship traffic density	No. of ships	0	1-2	3-5	6-10	11-20	21-30	31-40	>40

2.3. Oil spill model

In the present version of the oil spill 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) seawater characteristics (density and temperature), and (v) the spill locations that are determined by the accident model. The particle tracking method is employed to model the advection-dispersion processes, and empirical equations 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 oil slick shape resembles an ellipse, described by equation (3):

$$A_s = \frac{\pi}{4} l_{min}\, l_{max} \text{ where } l_{min} = 53.76 \left(\frac{\Delta\rho}{\rho_{oil}}\right)^{1/3} V_o^{1/3}\, t^{1/4} \quad \text{and } l_{max} = l_{min} + 0.95\, U_w^{4/3}\, t^{3/4} \tag{3}$$

where A_s is the slick area (m^2); l_{min} and l_{max} are the lengths of the minor and major axes of the spill (m), respectively; $\Delta\rho = \rho_w - \rho_{oil}$, where ρ_w and ρ_{oil} are the densities of water and oil, respectively (kg m^{-3}); V_o is the initial volume of the spilled oil (barrels); U_w is the wind speed (knots); t is time (min).

Calculation of evaporation is based on the analytical expression proposed by Mackay, (1980), taking into account the ambient temperature T and the evaporation exposure parameter θ, which incorporates the initial volume and area of the spill and the mass transfer coefficient (MacKay and Matsugu, 1973). Time-dependent oil dissolution as well as emulsification are calculated also following Mackay, (1980). The rate of water-in-oil emulsification takes into account the influence of wind conditions, temperature and oil characteristics. The volume and density of the oil spill increases with time due to the interacting processes of dissolution, evaporation and emulsification and are specified by equations (4) and (5), by Guo and Wang (2009) and Buchanan and Hurford (1988), respectively:

$$V_{oil} = \frac{V_o\left(1-\left(F_e + F_d\right)\right)}{1-F_w} \tag{4}$$

$$\rho_{oil} = \rho_w F_w + \left(1-F_w\right)\left(\rho_o + K_b F_e\right) \tag{5}$$

where V_o is the initial volume of the spilled oil (m^3), ρ_{oil} is the density of the remaining oil and ρ_o is the initial density of the spilled oil (kg m^{-3}). The volume of the oil spill V_{oil}, the oil density ρ_{oil} and the new mass, $M_{oil} = V_{oil} \cdot \rho_{oil}$, are calculated in each time step using the above equations (4) and (5).

To simulate the advection and turbulent dispersive transport of the oil slick, a particle tracking method is employed. In each time-step, the new mass of the oil slick is divided into a number of particles and the random walk procedure is employed to simulate their trajectories due to advection and dispersion. Given the coordinates X^o, Y^o of a particle's position at the current time, the new position after Dt is calculated by adding the displacements in the x and y directions (Chao *et al.*, 2001):

$$DS_X = U_{surf}\ Dt + DS\cos\theta \quad \text{and} \quad DS_Y = V_{surf}\ Dt + DS\sin\theta \tag{6}$$

$$DS = \left[R\right]_0^1 \sqrt{12 D_h\ Dt} \qquad\qquad \theta = 2\pi\left[R\right]_0^1 \tag{7}$$

where D_h is the horizontal dispersion coefficient (m^2 s^{-1}) accounting for turbulent diffusion and dispersion by waves, $\left[R\right]_0^1$ is a random number in the interval [0,1] and θ is a random direction angle (rad). The number of particles N and the oil mass M in each cell of the numerical grid can then be updated at every time-step.

2.4. Risk assessment model

The International Maritime Organization (IMO, 1997) defines the maritime risk as a product of the accident frequency and the accident impact, that is:

Accident Risk = [Accident Probability] x [Accident Impact] (8)

In the present case, the risk analysis focuses on determining the relative risk between different geographic locations, notably on the coastal cells. The accident impact was determined by analysing the sensitivity parameters that include (i) Special Industrial Areas, such as 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, such as coastal natural gardens, protected areas, cultural areas, important habitat areas, sea meadow, important sea mammal and bird areas.

The accumulated oil mass in coastal cells can be computed by the OSM for each scenario. However, since in the present version the OSM accounts only for the behavior of the oil spill in the water body, calculations were stopped at time T*, when 10% of the particles representing the spill reached the coast (or the open boundary). This allows a preliminary relative estimate of the accumulated mass in each cell of the water body for the various scenarios considered, after the spill has reached the coast. All scenarios are weighted with the associated probability to determine the expected level of exposure of each coastal cell, which is defined as the (relative) accident impact index given on a scale of 1 through 6. The sensitivity factors are given as expert-based relative weights for different types of special areas (MRC 2010), as shown in Table 2. They are later multiplied by the oil impact factors and summed up to calculate the risk index (IMO, 1997).

Table 2. Sensitivity Factors

Special Economic Areas	1. Fisheries	7.56
	2. Blue flag beaches	7.67
	3. Industrial facilities	3.89
	4. Shipyards	2.89
	5. Load and passenger ports	3.44
	6. Marinas and slipway areas	4.00
Special Ecologic Areas	7. Coastal natural protected areas	8.00
	8. Coastal special protected environments	8.44
	9. Coastal natural and cultural areas	7.67

3. Applications

3.2. Saronicos Gulf

The Saronicos Gulf is located in east-central Greece, bounded by the coasts of Attica and Peloponnese and connected to the Aegean Sea to the south by an open boundary about 40 km long. The water depth is highly variable with some shallow areas, but also deeper parts with depths of about 400 m in the western part. The gulf geometry is also complex and includes several islands, the largest ones being Aegina, Salamina and Poros. Prevailing winds are from northerly directions. The Saronicos Gulf includes over 30 ports, the most important being the Port of Piraeus that is the largest and busiest port of Greece, handling mainly passenger ships; being in the vicinity of the capital city of Athens, plays an important role in the country's economy. Besides, there are several beaches and natural protected areas along the coastline. The hydrodynamic field was calculated by HYM on a 2.5x2.5 km grid for 49 wind scenarios: the case of calm and 48 scenarios of differing wind speed and direction (1-6$^+$ Beaufort for the 8 main wind directions). The large number of the scenarios to examine and the consequent heavy computational load was determinant for the selection of the grid size in this preliminary study.

Indicative results are shown in Figure 2(a) for one of the most common wind conditions, i.e. north wind of 4 bf. Figure 2(b) shows the relative accident frequency index for the Saronicos Gulf based on the factors listed in Table 1 and their associated probability of occurrence. As expected, the accident frequency index is highest in the vicinity of coastal areas, where the water is shallow and ship traffic is highest. Based on this map the four most probable accident locations were identified and used as input into the oil spill model. Considering the 49 circulation patterns and the four most probable accident locations identified previously, the OSM was applied to produce the oil slick transport and weathering processes for a total of 49x4=196 cases. In each case the initial spill was simulated by 10,000 particles corresponding to a volume of 1500 barrels of oil, equivalent to 197 t. The value of D_h used was 7 m^2 s^{-1}. Figure 2(c) shows the oil mass distribution in four instances of time (T*/8, T*/4, T*/2 and T*) after a spill at the entrance of Piraeus Port for the circulation pattern of Figure 2(a). Figure 2(d) shows the likely level of exposure to oil contamination expressed in terms of the relative accident impact index along the coast of Saronicos Gulf due to the 4 most likely oil spill accidents within the gulf. This risk map takes into account the cumulative effects of the different components of the model, namely: the probabilistic distribution of wind and the resulting current circulation patterns, the accident frequency analysis, the oil spill fate and transport predictions and the sensitivity of the coastal areas. The areas most at risk are the coastal areas near Piraeus Port, the north-western coasts of the island of Aegina, and the north-western part of the Gulf near the town of Isthmia.

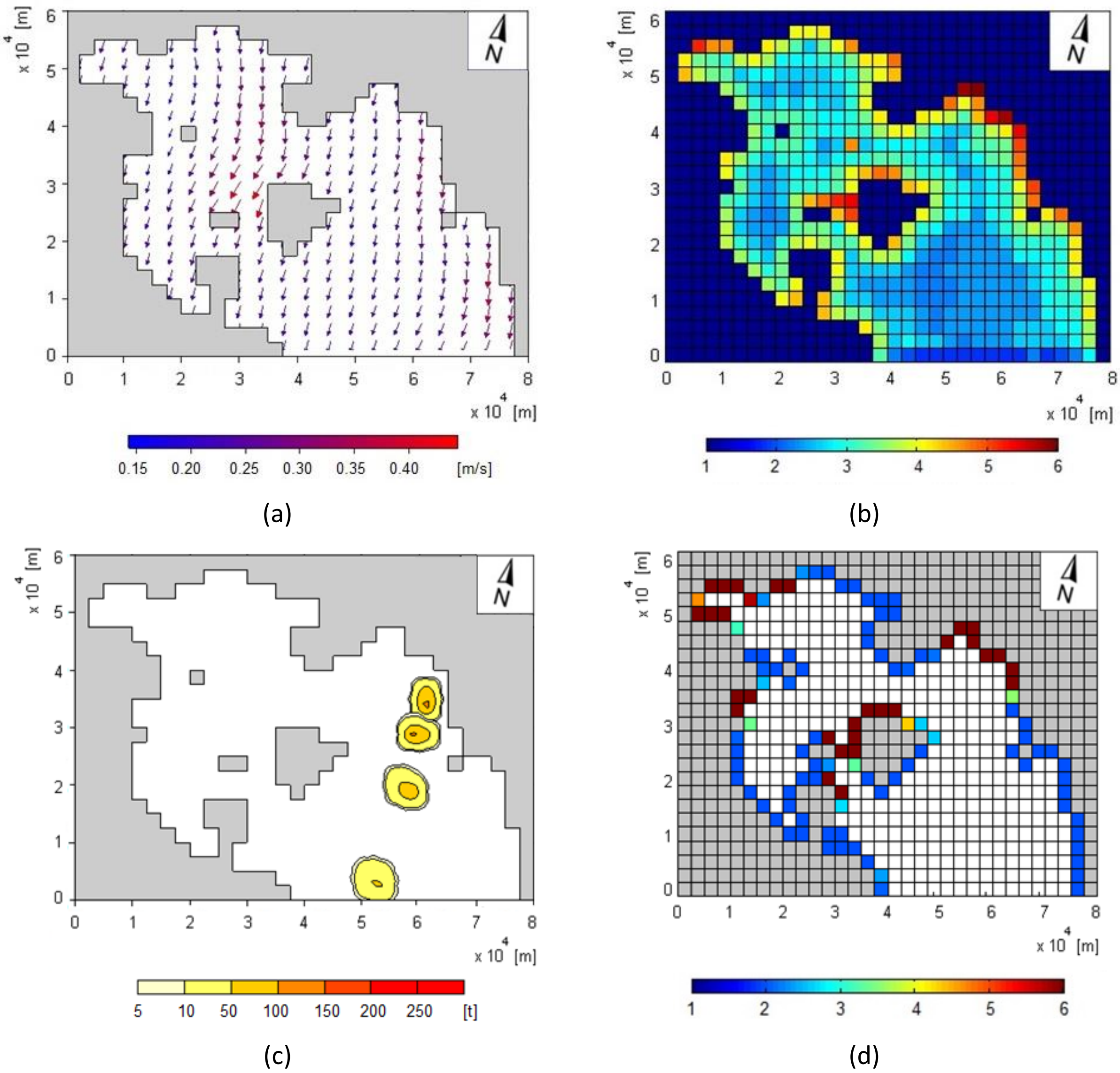

Figure 2. Model results for Saronicos Gulf: (a) Surface velocities for 4 bf North wind; (b) Relative accident frequency index; (c) Trajectory of oil spill at entrance of Piraeus harbor for North wind 4 bf; (d) Relative risk index of coastal segments

3.3. Izmir Bay

Izmir Bay includes the city of Izmir, which is the largest metropolitan area on the Aegean coast of Turkey. Izmir is also the main port of the area serving passenger and cargo ships but excluding tankers. The L-shape bay narrows down in the south-east direction exposing shoals and dangerous maneuvers. At its northern end, the Izmir Bay connects to the Aegean Sea through a 20 km wide open sea boundary. As in the case of the Saronicos Gulf, the HYM was run on a 2.5x2.5 km grid for 49 wind scenarios. Figure 3(a) presents the predicted currents for the Izmir Bay for one of the most common wind cases, i.e. east wind of 4 bf. Figure 3(b) shows the relative accident frequency index for the Izmir Bay based on the factors listed in Table 1 and their associated probability of occurrence. The accident frequency index is highest at the Alsancak Port (main port in the city) followed by the shallow passage near Yenikale Lighthouse, the Konak Limani and Guzelbahçe entrance. All four points are located in the southern part of the model domain where the Bay becomes narrower and ship maneuverability more treacherous.

These locations were then used as input into the oil spill model, and 196 OSM runs were conducted for the 49 wind scenarios and the four most probable accident locations which formed the initial spill conditions. Figure 3(c) shows the oil mass distribution in four instances of time (T*/8, T*/4, T*/2 and T*) after a spill at the Yenikale lighthouse for the circulation pattern of Figure 3(a). Figure 3(d) shows the relative accident impact index along the Izmir Bay coast due to the four most likely oil spill accidents within the bay. It is seen that the areas most at risk are the narrow passages leading to Izmir port at the southern end of the bay, the coast of Urla in the south-west, and the central eastern coastal areas of the Izmir Bay.

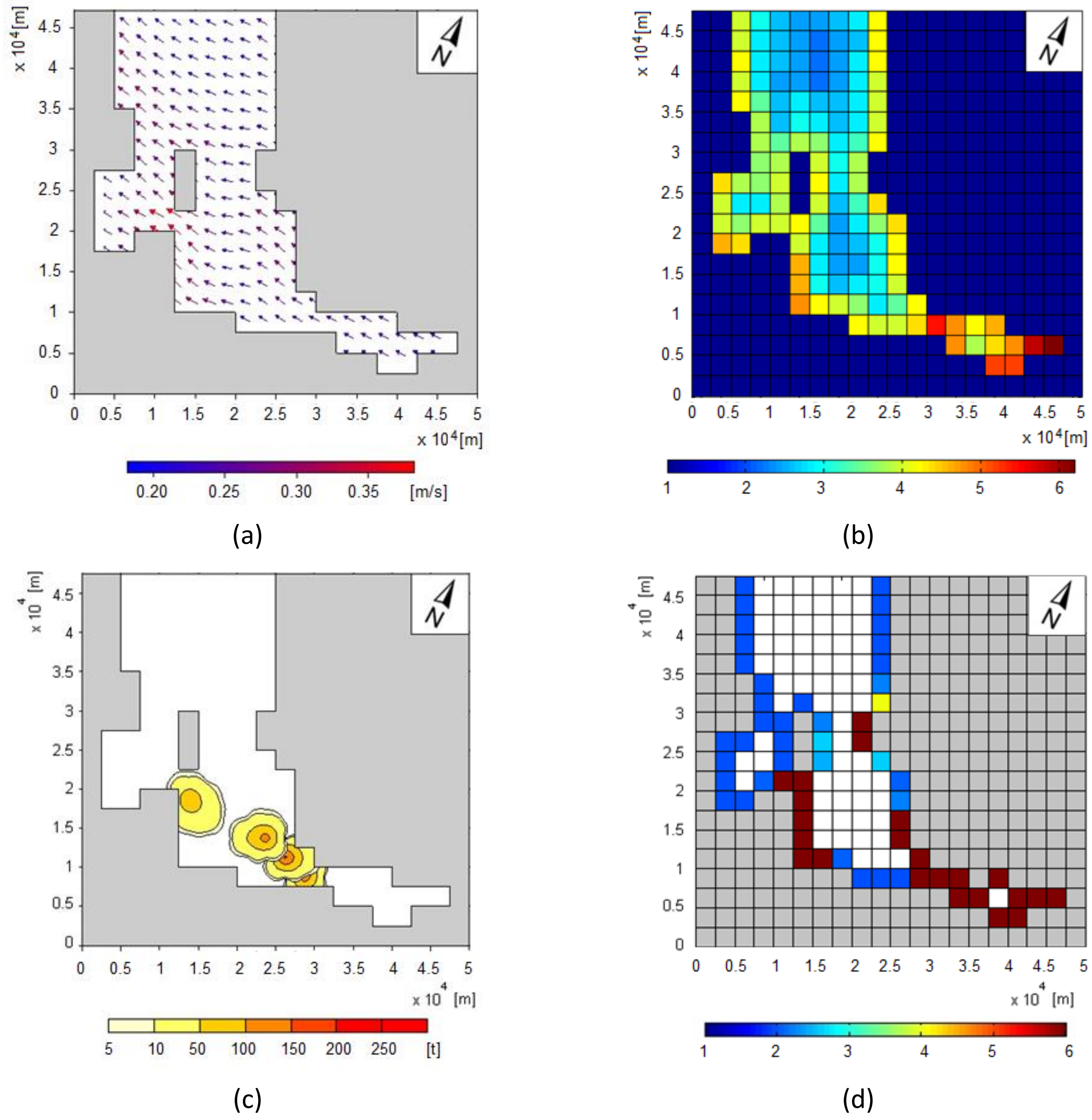

Figure 3. Model results for Izmir Bay: (a) Surface velocities for 4 bf East wind; (b) Relative accident frequency index; (c) Trajectory of oil spill at Yenikale lighthouse for 4 bf East wind ; (d) Relative risk index of coastal segments

4. Conclusions

An integrated model was developed combining physics-based hydrodynamic and oil spill computations and expert-based stochastic accident frequency evaluation and risk assessment in coastal areas. Given the difficulty of predicting future oil spill accident locations and the high level of uncertainty in the definition of the prevailing weather conditions, the modeling procedure is formulated within a stochastic framework. The focus of this paper is to present the integrated methodology developed and illustrate its potential application to two case studies. The results obtained should be considered as indicative, as they are based on several simplifications, such as (i) use of one-layer hydrodynamic model with empirical increase of surface velocities, (ii) no explicit inclusion of wave effects, (iii) use of coarse grid to allow the study of many scenarios as required input to the stochastic component of the model, (iv) neglect of some oil transformation processes. More accurate results can be achieved by employing finer computational grids and including more detailed description of the relevant phenomena in further model development. Although direct verification of the results obtained from the application of the model to the Saronicos Gulf and Izmir Bay was not possible due to lack of long-term statistics and spatial resolution of accident records, the concentration of high risk areas at both locations were identified, indicating that the busy ports with dense ship traffic and areas with navigational constraints expose higher risk. Such results, subject to further refinement, can be used to develop appropriate contingency plans in the event that an oil spill occurs.

The stochastic nature of the methodology provides a better and more reliable estimate of the oil spill risk in marine waters and thus may help reduce the threat of oil spill on the environment, considering not only the marine flora and fauna, but also the cultural, recreational and economic facilities along the coasts, such as ports, harbours, fish farms, ecologically sensitive areas, beaches, hotels, historic sites and other. The proposed methodology is expected to help law makers, public administrators and municipal planners in taking more effective measures to prevent and/or remediate future oil spills, e.g. by optimal location of Early Response Centres. Oil industry may also benefit from the reduced risk for their operations, whereas oil companies, insurance companies and tanker owners may reduce their operational costs. The methodology can be readily expanded to the entire Aegean Sea or other regional seas by adapting individual components to specific local conditions.

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