# RISK ASSESSMENT OF OIL SPILL ACCIDENTS PART 2: APPLICATION TO SARONIKOS GULF AND IZMIR BAY

**E.N. OTAY[1], A.I. STAMOU[2] , Y.C. ALTAN[1], G. PAPADONIKOLAKI[2], N. COPTY[1], G. CHRISTODOULOU[2], F.T. KARAKOC[3], V.K. TSOUKALA[2], D. KOUTSOYIANNIS[2] and A. PAPADOPOULOS[4]**

[1]Boğaziçi University, 34342, Bebek, Istanbul, Turkey.
e-mail: otay@boun.edu.tr
[2]School 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
[3]Tübitak Marmara Research Center, Gebze, Kocaeli, Turkey.
e-mail: fatma.tellikarakoc@tubitak.gov.tr
[4]Institute 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

In a companion paper (Stamou *et al*., 2013) an integrated mathematical model was presented for the assessment of oil spill risk due to maritime accidents. The model consists of four parts: (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.

In the present paper, the model is applied to two areas: the Saronicos Gulf, Greece and Izmir Bay, Turkey. The main criteria for case selection were the busy maritime traffic in both areas and the fact that the two large metropolitan areas of respective countries are located in these bays. The flow fields in both 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

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, 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, occurring at the Ionian and the Aegean Sea, respectively, ranked within the top 12 in the world. While the Alaska spill initiated environmental research and legislative changes in the world, the Ionian and Aegean waters are still unprotected against a disaster.

A number of mathematical models have been developed to simulate the fate and transport of oil spills in marine environments. These models can estimate the oil trajectory of an individual oil spill event and predict the distribution of the oil within the different environmental components such as the surface water, atmosphere, water column, sea bottom and coastal segments (e.g. Mackay, 1980; Tan and Otay, 1999; Wang *et al.*, 2005, 2008; Zadeh and Hejazi, 2012). Although such models are very useful for the evaluation of impacts of oil spills, they are generally applicable to particular oil spill events and specific to prevailing weather and environmental conditions at the time of the accident. There is an urgent need to develop mathematical tools that can highlight the coastal areas that are most susceptible to oil spill accidents. Such endeavors are particularly needed for the development of national and international oil spill contingency plans (e.g. SafeTec, 1999; MRC, 2010).

In a companion paper, Stamou *et al.* (2013) describe a methodology for assessing the risks associated with marine oil spill. The present paper is an application of the proposed methodology to coastal areas within the Aegean Sea; the Aegean Sea is known for its historically busy maritime traffic with navigation hazards, manoeuvre constraints and economically and ecologically sensitive coasts. The present study quantifies the contamination risk at surrounding coasts and help to prepare contingency plans against a potential disaster with trans-boundary impacts. Saronicos Gulf and Izmir Bay are selected at the present time as pilot sites to assess the maritime accident and oil pollution risk for the adjacent coasts.

## 2. IMPLEMENTATION OF METHODOLOGY

### 2.1. Accident Frequency Index

The relative accident risk in the present model is described with a Bayesian network model proposed by Uluscu *et al.* (2009) who calculated the relative risk in a geographic segment. Conditional probabilities of accident factors are determined from interviews and questionnaires with experts and calibrated with past accident data where available. This approach elaborates on the statistical character of vessel traffic and accident causes; however, in Uluscu *et al.* (2009) the occurrence of the accident and the resulting physical processes involving the propagation and fate of oil spill were not thoroughly considered. In the present work, this approach has been extended by modeling the post-accident processes with an oil spill modeling technique (OSM; Stamou *et al.*, 2013), which is run for a realistically large set of scenarios, representing a mutually inclusive set of possible realizations.

As a first step, meteorological records of case study regions were analyzed to determine the probability distribution of wind, which is the primary driving force on water currents in both model domains. The joint probability mass functions of wind speed and direction were 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, a total of 49 scenarios were analyzed with associated probabilities to be used as input conditions into the hydrodynamic model (HYM).

The resulting spatial distribution of surface currents from the 49 scenario runs were 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 constitution of the emergency response centers and contingency plans for Turkish coasts. As an example, the factor based on the current speed is selected as the probability that the surface current in a particular cell is exceeded by the critical current velocity ($V_{cr}$), which is equivalent to moderate breeze (Beaufort scale 4) and is defined as the threshold for the surface current starting to impact the navigation of the vessel.

**Table 1.** Factors affecting accident frequency index (associated with hydrographic and navigational characteristics of marine cells).

| Cell Characteristic | | Relative Index 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| Current magnitude | Pr (Vmax > Vcr) | 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) | Pr ($A_{5m}$ < $A_{tot}$) | 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 |

Applying the factors in Table 1, to each grid cell of the computational domain, the relative accident frequency index is determined and its spatial distribution is then used for the selection of the most probable accident locations in the application areas. Each probable accident location is used as an initial spill location in the OSM scenarios using spill parameters most likely to occur in regional oil accidents, including the spill volume and oil properties.

In the present study, the accumulated oil mass in coastal cells was computed separately by the OSM for each scenario and the calculations were stopped when the 10% of the initial spill reached the coast. All scenarios were weighted with the associated probability to determine the expected level of exposure of each coastal cell, which is defined as the accident impact index given on a scale of 1 through 6.

### 2.2. Coastal Sensitivity Factor

The sensitivity of the coast to oil contamination is summarized in terms of the existence of special economic and ecologic areas for each coastal domain. The sensitivity factors are given as expert-based relative weights for different types of special areas (MRC, 2010). They are later multiplied by the oil impact factors and summed 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 Ecological Areas | 7. Coastal natural protected areas | 8.00 |
| | 8. Coastal special protected environments | 8.44 |
| | 9. Coastal natural and cultural areas | 7.67 |

## 3. SARONICOS GULF

### 3.1. General characteristics

The Saronicos Gulf is located in east-central Greece, bounded by Attica and Peloponnesus coasts and connected to the Aegean Sea to the south by an open boundary about 40 km long, extending from cape Sounion to the coast of Peloponnesus. 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 of different uses; the most important is 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, it plays an important role in the country's economy. Besides, there are several beaches and natural protected areas along the coast of the Saronicos Gulf.

### 3.2. Hydrodynamic calculations

The hydrodynamic field was calculated following the methodology of Stamou *et al*. (2013) 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). Indicative results for the Saronicos Gulf are shown in Figure 1 for two of the most common wind conditions; the northern and southern wind with velocity magnitude equal to 4 and 3 bf respectively.

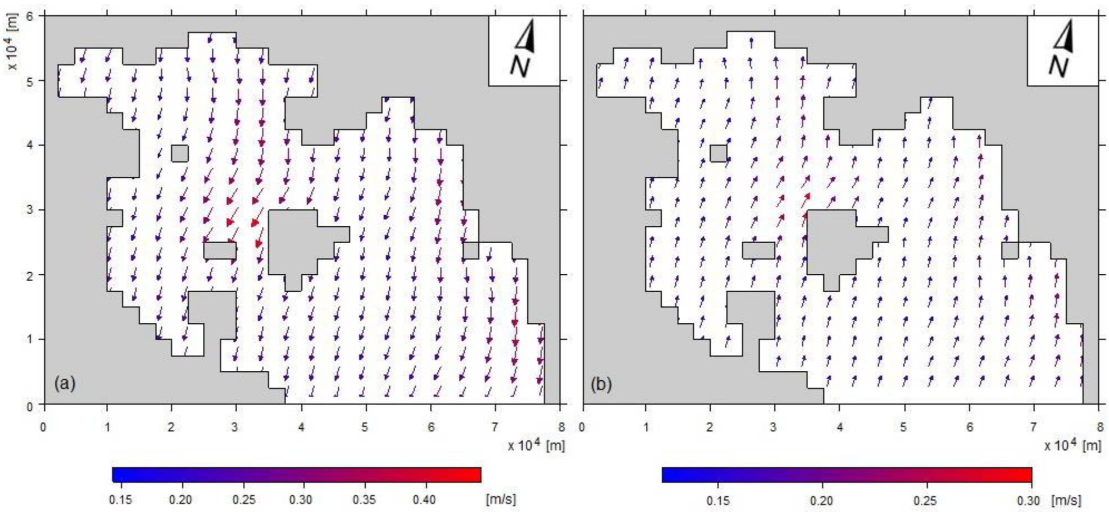


**Figure 1.** Saronicos Gulf surface currents for (a) N wind – 4 bf, (b) S wind – 3 bf.

### 3.3 Accident Frequency Analysis

Figure 2 shows the 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 where 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.

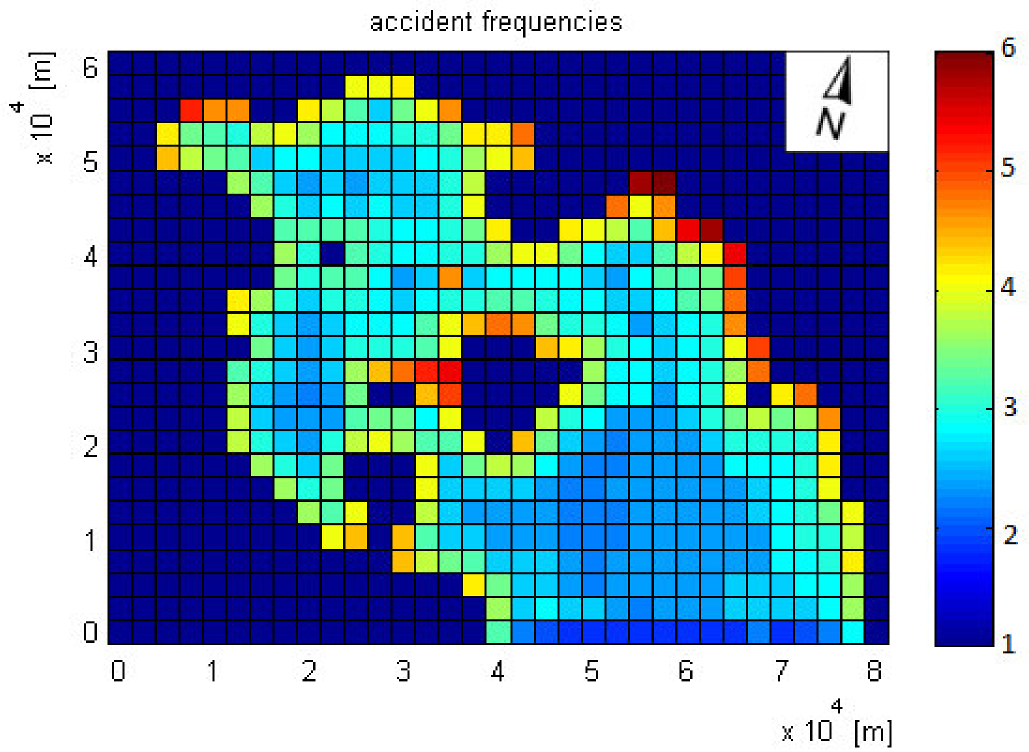


**Figure 2.** Accident frequency index for the Saronicos Gulf.

### 3.4 Oil Spill calculations

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. Indicatively, Figure 3 shows the oil mass distribution in four instances of time after a spill at the entrance of Piraeus Port for the two circulation patterns of Figure 1.

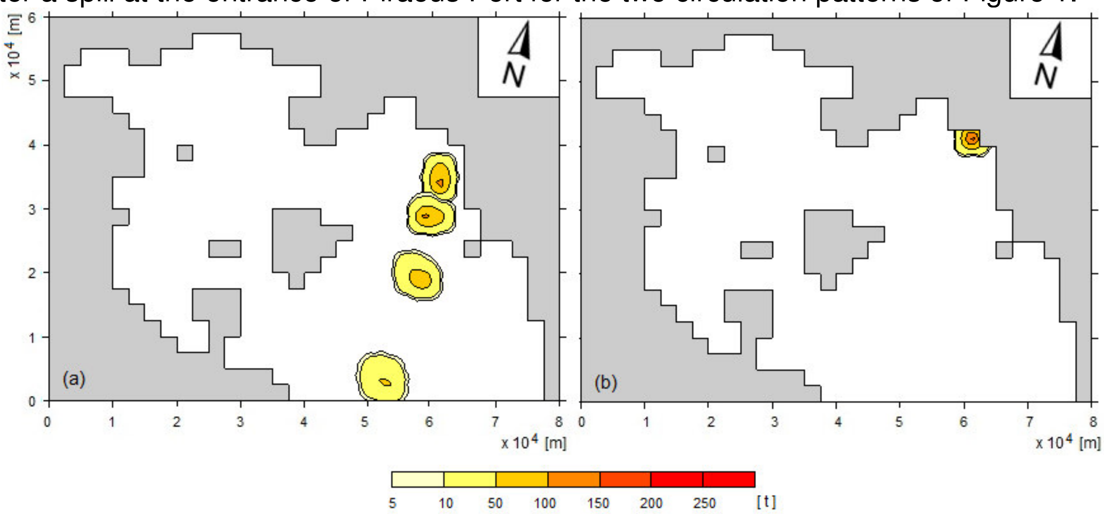


**Figure 3.** Saronicos Gulf oil slick trajectories for (a) N wind – 4 bf, (b) S wind – 3 bf.

### 3.5 Impact Analysis and Risk Assessment

Figure 4 shows the likely level of exposure to oil contamination expressed in terms of the accident impact index along the coast of Saronicos Gulf due 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 north-western end of the Gulf near the town of Isthmia.

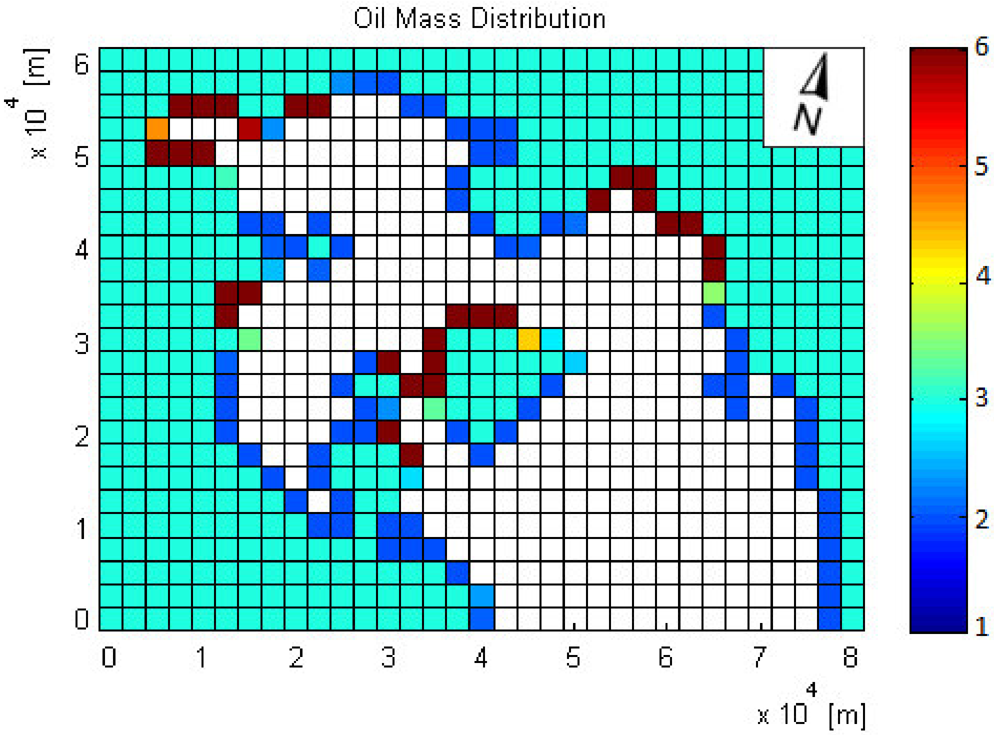


**Figure 4.** Accident impact index for the Saronicos Gulf.

## 4 IZMIR BAY

### 4.4 General Characteristics

Izmir Bay includes the city of Izmir; it 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.

### 4.5 Hydrodynamic calculations

As in the case of the Saronicos Gulf, the HYM was run for 49 wind scenarios. Figure 5 presents the predicted currents for the Izmir Bay for two of the most common wind cases; the eastern and northen-western wind with velocity magnitude equal to 4 and 2 bf respectively.

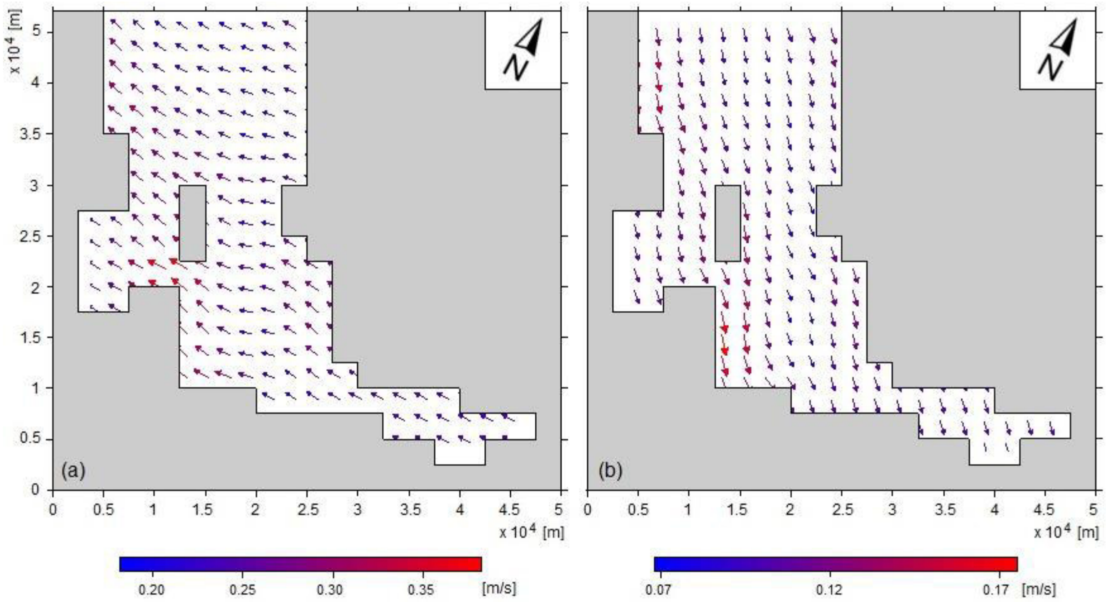


**Figure 5.** Izmir Bay surface currents for (a) E wind – 4 bf, (b) NW wind – 2 bf.

### 4.6 Accident Frequency Analysis

Figure 6 shows the 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. Based on this map the four most likely accident locations were identified at the Konak Limanı and Guzelbahçe entrance in addition to the two highest accident locations mentioned above. 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.

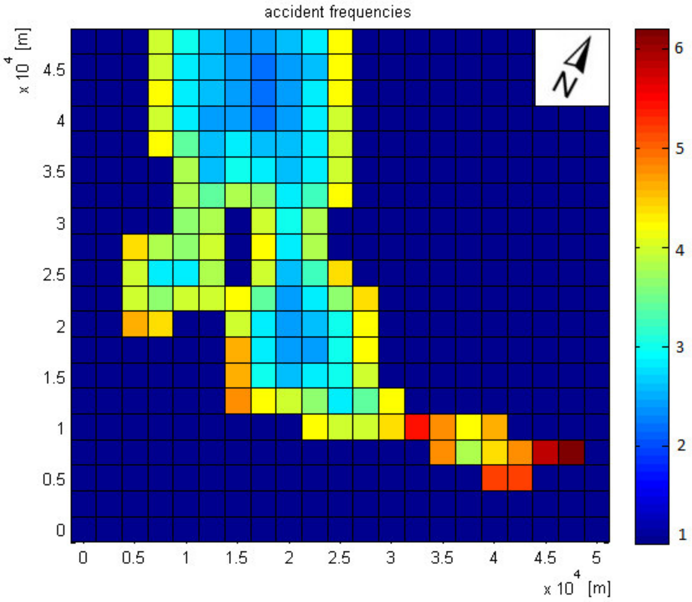


**Figure 6.** Accident frequency index for the Izmir Bay.

## 4.7 Oil Spill Calculations

Similar to the application for Saronicos Gulf, the 196 OSM runs were conducted for the 49 wind scenarios and the four most probable accident locations which formed the initial spill conditions. Figure 7 shows the oil mass distribution in four instances of time after a spill at the Yenikale lighthouse for the circulation patterns of Figure 5.

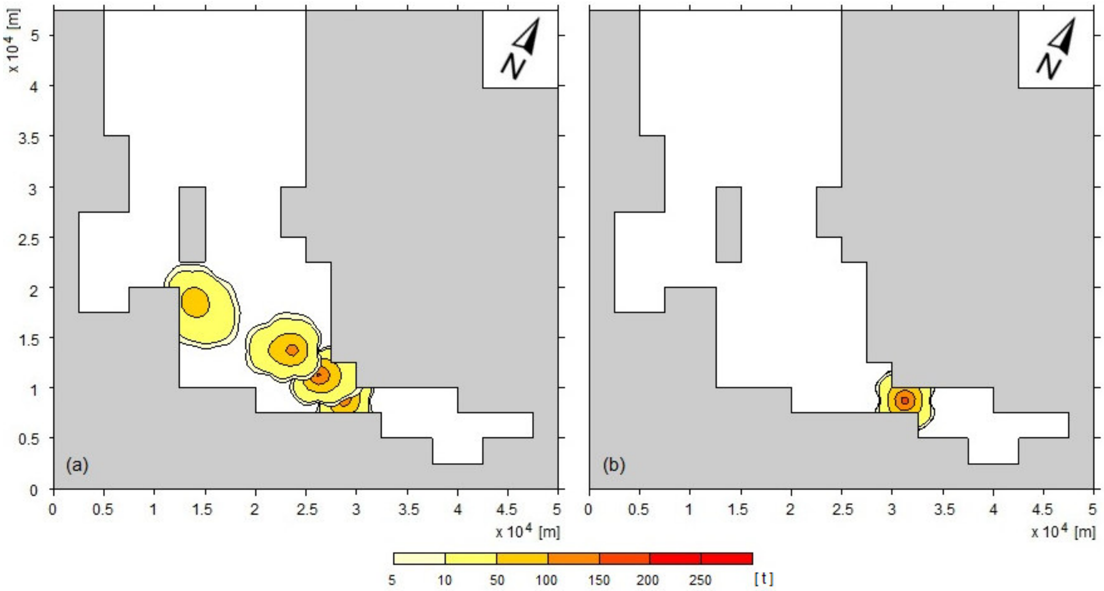


**Figure 7.** Izmir Bay oil slick trajectories for (a) E wind – 4 bf, (b) NW wind – 2 bf.

## 4.8 Impact Analysis and Risk Assessment

Figure 8 shows the accident impact index along the Izmir Bay coast due to the four most likely oil spill accidents within the bay, taking into account the cumulative effects of the different components of the methodology. The areas most at risk are the narrow waters 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.

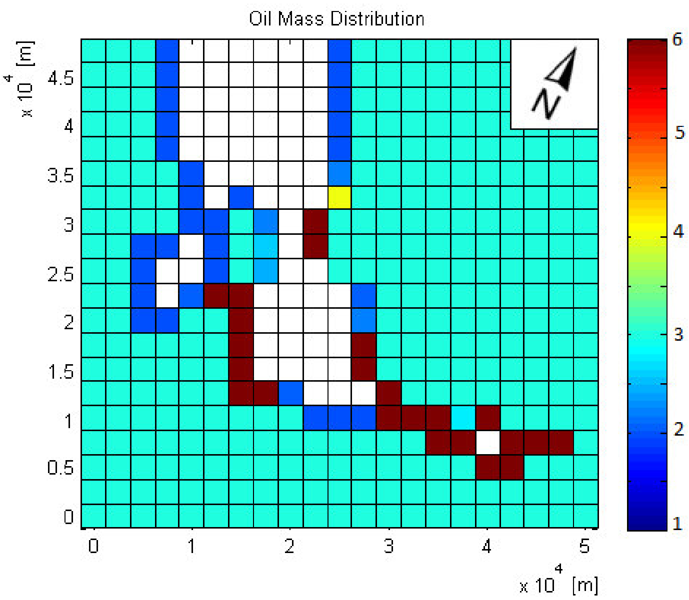


**Figure 8.** Accident impact index for the Izmir Bay.

## 5 DISCUSSION AND CONCLUSIONS

An integrated model was developed to perform physics-based hydrodynamic and oil spill computations and expert-based stochastic accident and risk assessment in the Saronicos Gulf and Izmir Bay. Although a direct verification of the results were 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 known areas with navigational constraints expose higher risk. Such results can be used to develop appropriate contingency plans in the event that an oil spill occurs within the Aegean Sea.

The methodology presented in Stamou *et al.* (2013) and the two applications described in the present paper highlight the need to develop an integrated approach for the identification of the coastal regions most susceptible to oil spills. Such an approach must include the development of hydrodynamic and oil spill fate and transport models with input from different experts, such as naval architects and maritime specialists, ecologists, marine biologists, and economists to assess accident frequencies and their impacts on the coastal and marine environments. Given the difficulty of predicting future oil spill accident locations and the high level of uncertainty in the definition of the prevailing weather conditions, it is imperative that the entire problem be formulated within a stochastic framework.

Further work is needed to expand the methodology to the entire Aegean Sea. Moreover, an important feature of the proposed framework is that it can be readily applied to other regional seas by adapting individual components of the methodology to specific local inputs and conditions.

### 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 Greek General Secretariat of Research and Technology (GSRT) and the Turkish National Science Foundation (TUBITAK).

### REFERENCES

1. IMO (1997), Interim guidelines for the application of Formal Safety Assessment (FSA) to the IMO rule-making process, International Maritime Organization, MSC/Circ.829, MEPS/Circ.335, London, UK.
2. Mackay D. (1980), Oil Spill Processes and Models, Environmental Protection Service, Canada.
3. MRC (2010), Constitution of emergency response centers and determination of present situation of Turkish waters for feasibility studies; national and regional contingency plans, Spec. Rep. prepared by Tubitak Marmara Research Center, Gebze, Kocaeli.
4. SafeTec (1999), Identification of Marine Environmental High Risk Areas (MEHRA's) in the UK, Report prepared for the Dept. of the Environment, Transport and the Regions, Doc. No.: ST-8639-MI-1-Rev 01, UK.
5. Stamou A.I., Otay E.N., Tsoukala V.K., Copty N., Karakoc F.T., Christodoulou G., Papadopoulos A., Papadonikolaki G. and Altan Y.C. (2013), Risk assessment of oil spill accidents, Part 1: Presentation of the methodology, 13th International Conference on Environmental Science and Technology (CEST2013), September 5-7 2013, Athens, Greece.
6. Tan B. and Otay E.N. (1999), Modeling and analysis of vessel casualties resulting from tanker traffic through narrow waterways, *Naval Research Logistics*, **46**(8), 871-892.
7. Uluscu O.S., Ozbas B., Altiok T. and Or I. (2009), Risk Analysis of the Vessel Traffic in the Strait of Istanbul, *Risk Analysis*, 29:1454-72.
8. Wang S.D., Shen Y.M. and Zheng Y.H. (2005), Two-dimensional numerical simulation for transport and fate of oil spills in seas, *Ocean Engineering*, **32**, 1556-1571.
9. Wang S.D., Shen Y.M., Guo Y.K. and Tang J. (2008), Three-dimensional numerical simulation for transport of oil spills in seas, *Ocean Engineering*, **35**, 503-510.
10. Zadeh E.S. and Hejazi K. (2012), Eulerian Oil Spills Model Using Finite-Volume Method with Moving Boundary and Wet-Dry Fronts, Modelling and Simulation in Engineering, 2012(33), Article ID 398387, 7 pages, doi:10.1155/2012/398387.