

## Coastal Risk Modelling for Oil Spill in The Mediterranean Sea

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### ABSTRACT

The accident probability estimation and the consequence analysis are based on statistical data about oil spill accident occurrence in the Mediterranean area, on the probability of different release sizes, and on the joint probability of wind speed and directions.

The risk model and its evaluation have been assessed for the Mediterranean littoral considering the time required by the oil slick to hit the coast in specific sensible target points assuming that an oil release accident potentially occurred in an accident sites located along the ship routes.

This approach has been applied on the area of the Strait of Gibraltar, which supports a significant volume of maritime traffic because it represents the navigational connection channel between the Atlantic Ocean and the Mediterranean Sea.

## 1. Introduction

The environmental risk analysis is increasingly used in the sector of maritime life, and many studies have been conducted in the framework of the maritime risk assessment with special attention to the hazardous material transportation [1,2]. Risk can be defined as a measure of an accident occurrence potentiality as well as its gravity [3]. In fact, risk analysis is widely acknowledged as a process for depicting risk systematically and scientifically [4,5]. The main objective of risk analysis is to prohibit the occurrence of accidents [1]. In order to define high-risk areas, it is necessary to quantify both the absolute level of risk and the relative significance of the different causes [6,7].

In recent decades, several methods and applications have been reported in the literature for maritime transport risk analysis. These approaches attracted growing interest both from international organizations that have suggested the use of specific risk analysis and management tools [8,9], and from researchers who focused on fundamental issues relevant to risk assessment. From the academic

viewpoint, the main topics referred to terminology, concepts and perspectives of risk analysis and management in the maritime context [10–25].

In [26], the authors proposed an environmental approach to assess the risk in a maritime area. In [27], the author presented a method to quantify the uncertainty related to traffic data in maritime risk assessment. The work in [6] defined the framework for risk analysis in a maritime area through a case study of RoPax vessels. In [28], the authors applied the so-called FMEA, failure mode and effects analysis method, for the risk of ship collision in a maritime area. The authors in [29] and [30] quantified the effect of risk reduction measures for the shipping in a waterway area. In [31], the researchers determined the relative risk of various coastal areas. Some studies determine the probability and consequences of a shipping accident [32, 33].

In the literature, specific works focused on the oil spill modelling. In [34], the authors developed a Lagrangian model to determine the trajectory of the oil spill on the Patos Lagoon in Brazil, considering factors influencing the region such as coastal ocean

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currents, wind currents, tides and river flows. Another similar study proposed in [35] identified sensitive areas in a bay in the event of a hazardous substance spill accident. The work in [36] presented a model based on a Lagrangian approach to identify the areas most exposed to pollution risk in the Baltic Sea, Finland. In [37], a study has been carried out to protect the marine environment in the Bohai Bay region from spill accidents. This study simulated oil spill transport and fate in sea based on the particle approach.

Other studies examined oil spill modelling tools. The authors in [38] analyzed two tools for the deepwater region of the Campos Basin, Brazil: the General NOAA Operational Modeling Environment (GNOME) used by the Emergency Response Division of the Office of Response and Restoration (OR&R) and the Python Operational Ocean Forecasting Engine (OOFE).

Other approaches exist to estimate oil slick weathering. MEDSLIK predicts the oil spill on the surface of the Mediterranean Sea [39]. POSEIDON-OSM simulates evaporation, emulsification and sedimentation processes. It is used for the Greek Sea [40], the Baltic Sea [41], and the Aegean Sea [42,43]. ADIOS (Automated Data Inquiry for Oil Spills) is NOAA's oil weathering model. ADIOS models how different oil weathering processes occur in the marine environment. It has been used by many authors [44,45].

The oil spill is one of the most dangerous sources of pollution that threaten maritime safety because of its serious consequences to the ocean environment and the ecosystem as well as enormous economic losses and society impact [46–52].

A released petroleum product is subject to the effects of the environment which generates its dispersion in the marine environment and, simultaneously, it modifies its physical and chemical characteristics, the so-called "weathering" of the oil [53]. The behavior of oil drift at sea is the result of a set of interactions that occur between the spilled product and the external environment conditions [54]. When hydrocarbons are discharged at sea, they suffer a large number of transformation processes: drift and spreading, evaporation, dissolution, dispersion, emulsification, photo-oxidation, biodegradation, sedimentation, pouring, stranding and interaction with sea ice. While some processes are currently well-understood, such as spreading and evaporation, others remain poorly known (photooxidation and biodegradation) [54–57].

The risk of oil spill pollution in the Mediterranean Sea is high due to the significant traffic of oil and gas [58], where are listed more than 100 million gallons of crude oil spilled annually [59,60]. Statistically, 52 % of total oil spills in the Mediterranean come from shipping, compared to 48 % for other seas [61].

In case of an oil spill accident in the marine environment, it is mandatory to know the trajectory (movement and spreading) of the pollutant slicks under various weather conditions, so as to organize the oil recovery operations and to protect the areas exposed to the risk of pollution [62,63].

This paper provides an approach to rapid mapping for the analysis of the risk addressing the accidental of maritime transportation in a Strait of Gibraltar in the Mediterranean Sea. The purpose of the proposed paper is twofold. Firstly, it aims at defining a simple

methodology to classify the risk in marine and coastal areas due to maritime hazardous material transportation. Secondly, the proposed approach provides a useful tool that can support spill response teams and other operators in facilitating oil spill planning and preparedness.

The following section of the paper represents a review of the main shipping accidents which generated massive oil spills in the Mediterranean Sea. The third part introduces the proposed oil spill model, where a Lagrangian model has been proposed to identify risk areas that could be affected in the occurrence of a spill accident. The proposed model was applied to the real case occurred in the Mediterranean Sea toward the French coast in October 07, 2018, and the results have confirmed the reliability and relevance of the proposed model. In section 4, the application of the proposed model is described in the context of a potential maritime accident in the Strait of Gibraltar in the Mediterranean Sea. In section 5, the potential environmental risk was assessed on the basis of the time required by the oil slick to reach the coasts in the Strait, lastly, in section 6, conclusions.

## 2. State of art in the Mediterranean Sea

The Mediterranean Sea is a tragic theater of maritime accidents. In 1991, the Haven disaster in the coastal area of Genoa in Italy, which produced the release of 144,000 tons of hydrocarbons, has been ranked as the fourth most dangerous event among global shipping accidents [64,65]. In addition, the Mediterranean is threatened by accidents occurring outside its geographical area. For example, the maritime accident that occurred in the Atlantic Ocean as a result of a collision between the oil tanker «Seat Spirit», which was carrying heavy oil, and «Hesperus», which transported chemical products, caused a spill of 12,200 tons of oil. However, depending on weather conditions (wind speed and ocean currents), the contaminants were transferred by the Strait of Gibraltar to the Moroccan, Spanish and Algerian coasts [66-68].

Table 1: Number of oil spill accidents in the Mediterranean Sea between 1977 and 2019 (REMPEC, 2019).

Years	Number of accidents	Type of pollutant	
		Volatile Oil	Non-volatile Oil
Between 1977 and 1987	46	3	43
Between 1988 and 1997	73	5	68
Between 1998 and 2007	28	3	25
Between 2008 and 2019	124	82	42

According to recent statistics from the “Alerts and Accidents database” (REMPEC) [69], containing data on spills (quantity, type of spilled oil, location and on the ships involved), 268 tankers were involved in maritime accidents in the Mediterranean Sea, 93 accidents for “Volatile Oil” and 178 for “non-Volatile oil”, as shown in the table 1.

The aforementioned statistics shows that, the number of accidents involving accidental spills decreased between 1998 and 2007, with 46 and 28 accidents occurred respectively. This reduction can be

attributed to the implementation of international, regional and national legislations and, precisely, at the level of European countries. The European Union has put in place a series of strict measures (Erika I and Erika II)[70,71] to control ships entering in the European ports. Also, the new technologies application in the shipbuilding industry improves the quality and safety of this mean of transport [61]. Nevertheless, between the years 2008 and 2019, the number of accidents increased again especially in Greece maritime area where the 90% of Mediterranean oil spill accident ensued. Greece holds the record for oil spilled in the main accidents, with 378,027 tons, followed immediately by Italy with almost 364,823 tons and Spain with 333,492 tons [69].

Accidents occurring in the European sea area are more frequent than in other parts of the Mediterranean: on 268 accidents in the Mediterranean Sea, 232 involved European Mediterranean countries. This can be attributed to the increased trade and traffic and to the presence of the petrochemical industries on the coast: in Italy, as an example, there are 14 oil ports and 17 refineries [61]. The high maritime traffic density between Gibraltar and Sicily reflects the importance of the Western Mediterranean as a transit zone [72,73].

2.1. Statistics about oil spills from tank vessels

Oil spills are generally classified according to the estimated amount of released products. The different release sizes can be classified into three categories as follows:

spills smaller than 7 tons, spills with releases between 7 and 700 tons or spills greater than 700 tons. This information is available on several databases as REMPEC [69] or ITOPF [74], which contains data about 10,000 accidents: the most frequent events (84%) belong to the smallest category with releases inferior to 7 tons [74].

The table 2 shows that the number of large spills (> 700 tons) has decreased significantly over the last 20 years. The average number of large spills per year during the 2000s was less than one-third of the one observed during the 1980s.

Most accidents result from a combination of different causes and circumstances which contribute in different ways to the final event. These causes can be categorized as "operational" and "accidental" [75-77]. From the table 3, it may be noticed that:

- tanker spills in the Mediterranean Sea mostly come from accidental causes such as stranding, collisions and shipwrecks, which generally generate larger spills;
- tanker spills which result from habitual operations such as loading, unloading and bunkering normally occur at ports or in the oil terminals;
- the majority of these spills are small or medium-sized, approximately 53% of the accidents for quantities between 7 and 700 tons.

The Figure 1 summarizes the causes of spills in the Mediterranean Sea between 1977 and 2019.

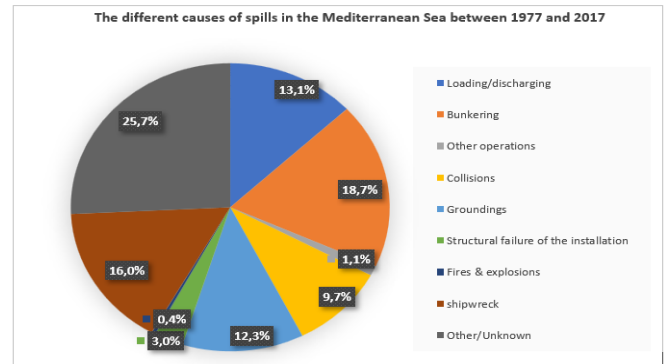


Figure 1: The different causes of spills in the Mediterranean Sea between 1977 and 2019. (REMPEC database).

3. A Lagrangian-based maritime and coastal risk model formulation

In the literature, the oil spill represents one of the main concerns in the context of risk analysis of maritime transportation due to the potential impact on marine ecosystems, to socio-economic activities and to the huge efforts in terms of recovery and clean-up operations [78-80].

Different risk definitions exist in the literature involving components such as probability, uncertainty, frequency of specific events, and/or related consequences. In [81], a review of methods and applications for maritime transportation risk analysis have been presented.

Table 2: Number of accidents and amount of spilled oil in the Mediterranean, between 1977 and 2019 (Source: REMPEC database)

Quantity spilled (tons)		Time horizon			
		Between 1977 and 1987	Between 1988 and 1997	Between 1998 and 2007	Between 2008 and 2019
<7	Number of spill accidents	20	36	17	51
	Total Quantity (t)	31	57	18	271
7<x<700	Number of spill accidents	18	31	9	63
	Total Quantity (T)	2595	5150	1835	9378
>700	Number of spill accidents	8	6	2	10
	Total Quantity (T)	283170	151700	3000	74700

In the proposed approach, the risk ( $R$ ) is associated with the expected value of the probability ( $P$ ) of an accident occurrence with a given spill size in a specific sea area and to the outcome arising as a consequence ( $C$ ) of the oil slick movement [47],[81]. The risk (*Risk*) is defined as a function of accident probability ( $P$ ) and consequences ( $C$ ) for the specific transportation hazard scenarios [82]:

$$Risk = f(Probability, Consequences, Scenario(s)) \quad (1)$$

Table 3: Number of oil spill accident according to spill size and operational/category causes in the Mediterranean, between 1977 and 2019 (REMPEC 2019)

Type of spill	Quantity spilt (Tons)			Total
	<7	7 < x < 700	>700	
<b>Operational</b>				
Loading / unloading	17	16	2	35
Leaking oil or gas	10	36	4	50
Other operations	2	1		3
<b>Accidental</b>				
Collision	8	13	5	26
Grounding	22	8	4	34
Structural failure of the installation	3	5		8
Fire or explosion	1	0	1	2
Shipwreck	22	17	4	43
Other	39	25	6	70

### 3.1. Accident probability analysis

The probability of maritime traffic accident occurrence is usually modelled by statistical approaches which are based on historical documentations about accident and non-accident rates, failures equipment, spill or release probabilities and container designs.

In the proposed model, the oil spill probability  $P_{i,s,h}$ , at the marine location  $i$ -th, for a specific spill size  $s$ -th, according to the weather scenario  $h$ -th generated by different meteorological conditions, is computed through the combination of three different components:

$$P_{i,s,h} = AR_i \times P_s^{spill\ size} \times P_{i,h}^{weather} \quad (2)$$

where:

-  $AR_i$  is the yearly oil spill accident rate for a specific water area which the location  $i$ -th belongs to. Assuming to be known a set of statistical data for a limited time horizon about accidents occurred in a predefined sea area,  $AR_i$  may be computed as:

$$AR_i = \frac{\# oil\ spill\ accident}{\# years * area} \left[ \frac{\# accident}{yr\ km^2} \right] \quad (3)$$

-  $P_s^{spill\ size}$ , is the probability of different release sizes in case of the accident occurrence. Three release sizes  $s$  were defined (small, medium, and large). These release sizes dictate the probability of the size of release in the probability analysis and in the consequence analysis.

$$P_s^{spill\ size} = \frac{\# accidents\ for\ the\ category\ of\ oil\ spill\ size\ s}{\# Total\ accidents} \quad (4)$$

-  $P_{i,h}^{weather}$ : the probability of weather stability, in the location  $i$ -th, for the weather scenario  $h$ -th, represents the probability of different combinations of atmospheric conditions for wind speed and wind directions based on frequency analysis. Statistical data are available in open-source database for different Mediterranean areas [83].

### 3.2. Consequence modelling

Currently, the consequence modelling is classified into two generations models according to their analysis in two or three dimensions (2D and 3D models). Those models have been developed to predict the evolution and behavior of hydrocarbons spilled on the surface and into the deepwater. The choice of dimension analysis directly influences the complexity of the model and the accuracy of the expected results. The 2D models [84–88] run quickly but they do not allow to obtain detailed information on the water column contamination [89] focusing only on the surface transport processes [90]. The 3D models [37], [39], [91] provide a description of the flow over the entire water column (surface, subsurface transport and fate processes) [90]. The latter models will give rise to more accurate results to simulate oil spills. Yet, more parameters have to be defined to get precise results. The decision to develop a 2D or 3D model strongly depends on the data that would be available to use as inputs. Upon the occurrence of a spill accident, the oil may stagnate as suspensions in the water column for a prolonged period due to the formation of emulsions. When emulsions processes are formed, the impact of the spill increases. As a consequence, the response and cleaning efforts become more complicated. Inclusion of the vertical movement of particles often makes the model very complex, as it will require detailed oceanographic information about the region for which the model is developed [92].

The 2D spreading models are mostly based on Lagrangian approaches [89]. The Lagrangian based models consider the oil slick as the movements of a set of small droplets subjected to wind, waves, and currents, and which can rise or sink due to buoyancy [93]. Several studies use the Lagrangian model to determine the areas that would be affected in the event of an oil spill [94–97].

In the proposed approach, a 2D Lagrangian based consequence model has been defined and used to compute maritime risk. The spreading, advection and diffusion processes which draw the oil spill trajectory and define consequently the impacted area of the spill accidents are described in the following paragraphs.

The vast majority of surface oil transport models use a random walk technique [46]. In this approach, the surface current field advects lagrangian elements representing the oil and disperses them through a random walk process used to represent horizontal dispersion.

#### 3.2.1. Spreading process

Spreading is one of the most relevant processes not only because it guarantees the prediction of the extent of oil slick area, but also, as it affects all other oil slick transformation processes.

Two physical phenomena lead to an oil slick movement on the surface water. First, the slick is subject to the spreading process under the influence of mechanical forces such as gravity, inertia, viscosity and interfacial tension and, on the other hand, to turbulent diffusion [53].

The oil slick extension in the wind direction is expected to increase with time proportionally to the wind speed, while the lateral elongation is always described by the gravity-spread equation proposed by [98].

$$A_0 = \pi \frac{k_2^4}{k_1^2} \left( \frac{V_0^5 g \Delta \rho}{\vartheta_m^2} \right) \quad (5)$$

where:

- $k_1$  and  $k_2$  are empirical coefficients ( $k_1 = 1.14$  and  $k_2 = 1.45$  [99]);
- $V_0$  is volume of oil spilled (m<sup>3</sup>);
- $\vartheta_m$  is the kinematic viscosity of water (m<sup>2</sup>/s);
- $g$  is gravitational acceleration (m/s<sup>2</sup>);
- $\Delta \rho$  is the relative density difference between the water and oil given by:

$$\Delta \rho = \frac{\rho_w - \rho_{oil}}{\rho_w} \quad (6)$$

where  $\rho_w$  is the density of water (g/cm<sup>3</sup>) and  $\rho_{oil}$  is the density of oil (g/cm<sup>3</sup>).

In the next gravity viscous spreading phase, the area  $A(t)$  of the oil slick during the time horizon may be computed using a correlation developed in [100], which assumes that oil slick spreading may have an elliptical shape on the water's surface with the major axis oriented in the direction of the wind.

The area covered by the oil slick (m<sup>2</sup>),  $A_t$ , at time t-th, from the time  $t_0$ , is described by:

$$A_t = \frac{1}{4} \pi Q_t R_t \quad (7)$$

The length of the minor ellipse axis (m),  $Q_t$ , is given by (8):

$$Q_t = 1.7(\Delta \rho V_0)^{1/3} t^{1/4} \quad (8)$$

where  $V_0$  is the volume of oil spill in barrels, the time t-th is the number of time units starting from the time  $t_0$ . The length of the major axis of the oil slick ellipse (m),  $R_t$ , is described by:

$$R_t = Q_t + 0.03 * (U_{wind})^{4/3} (t)^{3/4} \quad (9)$$

where  $U_{wind}$  is the wind speed in Knots, and t is time in minutes.

### 3.2.2. Advection and diffusion

The transport of an oil slick is generally induced by surface currents, wind, waves and turbulent diffusion [55]. Wind and currents are the two major processes composing the phenomenon of advection the slick. This surface current is largely wind generated, but in high tides regions tidal currents may dominate.

In this two-dimensional model of oil spill, the initial area of oil slick is divided into a large number of distinct Lagrangian particles in a XY plane reference at the water surface where (x<sub>t</sub>, y<sub>t</sub>) represent the position of a particle at a time step t.

It is assumed that these particles are connected to the surrounding body of water and therefore diffuse from a random process. The advection and diffusion properties of each particle can be calculated based on the flow fields at the water surface and the wind speed. Consequently, the speed, as well as the displacement of these particles, can be solved. Once their coordinates are determined at each time step, the shape and trace of the spill can be decided.

#### 3.2.2.1. Advection velocity

A large number of models use a constant parameter to associate the surface wind speed to the drift of the slick. This parameter is taken equal to about 3.5% [100–106] of the wind speed. The oil slick is also supposed to drift on water at 3.5% of the wind speed combined with 100% of the current speed [100–106].

In the proposed model, the advective velocity ( $U_a$ ) of the oil slick due to wind ( $U_{wind}$ ) and surface current ( $U_{current}$ ) effects is given [100]:

$$U_a = U_{current} + 0.035 U_{wind} \quad (10)$$

where  $U_a$  is the advective velocity of the oil slick (m/s),  $U_{current}$  is the surface current (m/s) and  $U_{wind}$  is wind speed (m/s).

#### 3.2.2.2. Horizontal turbulent diffusion

The Lagrangian approach predominantly represents the turbulent diffusion considering that the surface and the suspended particles of the slick are subjected to a random movement in addition to the regular movement due to the main current in the sea [37].

The translations, during a time step  $\Delta t$ , respectively  $\Delta X_{diff}$  and  $\Delta Y_{diff}$  due to the diffusion phase of the particles in the X and Y directions are based on [100]:

$$\Delta x_{diff} = [R]_0^1 \sqrt{12 D_h \Delta t} \cos \theta \quad (11)$$

$$\Delta y_{diff} = [R]_0^1 \sqrt{12 D_h \Delta t} \sin \theta \quad (12)$$

where  $[R]_0^1$  is a random number between 0 and 1 from a uniform distribution,  $D_h$ : horizontal diffusion coefficient (m<sup>2</sup>/s); and  $\theta$  is the directional angle  $\theta = 2\pi [R']_0^1$ . (where  $[R']_0^1$  is a random number between 0 and 1).

So, the displacement of the oil slick due to advection and horizontal diffusion is given as [106]:

$$X_{t+1} = x_t + u_{a,x} \Delta t + \Delta x_{diff} \quad (13)$$

$$Y_{t+1} = y_t + u_{a,y} \Delta t + \Delta y_{diff} \quad (14)$$

where:

- $x_t, y_t$  is the location of the particles at time step t-th;

- $u_{a,x}$  and  $u_{a,y}$  are the advective velocities in the X and Y directions respectively;
- $\Delta t$  is the time-step interval (s);
- $\Delta X_{diff}$ ,  $\Delta Y_{diff}$  are the displacements of the particles in the X and Y directions respectively.

### 3.3. Model treatment

The main required variables for the development of this model are related to water depth, spill rate, hydrocarbon density, current direction, and current speed. The determination of spill thickness and approximated area covered by the spill is based on the calculations of the estimated volumetric flow rate of oil from the source which is input for the simulation. The spill coverage is deduced through the use of a correlation developed by [100], which illustrated the elliptical spreading of oil on the water's surface with the major radius oriented in the direction of the wind.

This model finds the solution for the spreading and advection process functions numerically developed at discrete time. It also calculates the overall mass of oil for each time step based on the mass lost due to weathering process. Other oil properties, such as density, may be also recalculated after each time step. All of the aforementioned parameters are technically functions of time. Yet, in order to comply with the aims of numerical evaluation, the surface area and the overall mass of the oil volume are considered constant during a given time step and then updated in the next time step to reflect changes in mass and density.

The re-calculation of the center of mass of the oil slick generates the new local coordinate system for the center of a new set of concentric ellipses. The Fay method [98] is considered as the base of the spreading rate algorithm gravity-viscous spreading formula adjusted to cover wind effects. During the gravity viscous phase, the elliptical spreading of the oil slick is calculated. It should be mentioned that the calculation is only fulfilled when the terminal oil slick thickness is reached (as an example 0.1 mm [102]). The terminal oil slick thickness results in the removal of the spreading assumption. Then, the slick is allowed to spread under the influence of horizontal diffusion, surface winds and water current shears to represent complex, realistic surface movements.

The accuracy of the proposed model depends on specific input data such as product properties (e.g. density), wind and current speed and direction data, as well as the effect of other physical or chemical processes during the spill accident that may play a role in the correctness of the model results.

The collection of the actual data is a constraint for the implementation of the model, however, the reliability of the proposed approach for the consequences modelling has been positively verified in [107]. This latter paper analyzed to the oil spill accident occurred at the coast of Saint Tropez (France) at 2018, October the 7th. The accident occurred due to the collision between a Cypriot container ship and a Tunisian vessel generating an oil release of 600 cubic meters in the Mediterranean Sea. The proposed consequence model, from eq. (5) to (14), replicated the movements and trajectories of oil slick on the sea surface with good accuracy. Both in real and simulated cases, the oil slick reached the French coast within 9 days.

## 4. Case Study: Strait of Gibraltar

Due to its strategical position and its busy maritime traffic, represents the main maritime highway in West Mediterranean. The Strait occupies the space where the dense commercial traffic fueling between Europe and Asia intersects, revealing the historical links between Europe and Africa. These flows raise the Strait of Gibraltar to the ranks of the Straits of Pas de Calais or Malacca in terms of international maritime traffic (97,000 to 100,000 vessels per year) and, besides, the nature of these flows makes it an observatory area of global trade [108].

In this study, it is assumed that the proposed oil spill model to simulate the evolution of an oil slick and to compute the related risk assessment are based on maritime accidents or accidental ship collisions which may occur in four different potential accident test sites (ATSS) in the body of water of the Gibraltar Strait. In detail, the four ATSS have been identified in the intersections of the ship routes which covered the study area (Figure 2). The proposed risk assessment model aims at evaluating the impact of the simulated accident scenarios on 8 sensible Point of Interest (POIs), potentially exposed to oil spills from tankers, located on the African and European coasts, namely Tanger, Port Tanger Med, Dalia beach, Oued Mersa beach, Ceuta for Africa, and Tarifa, Algeciras and Gibraltar for Europe. Figure 2 represents the geographical position of the selected ATSS and the locations of the sensible coastal Point of Interests (POIs). Table 4 shows the geographical coordinates of the ATSS and the related distances from the specific POIs on the Moroccan and Spanish coasts.

The proposed model considers the movement of oil slick and its approaches to the coasts. The risk evaluation is based on the time required to the oil slick to hit the coastline on a given POIs in different accident scenarios.

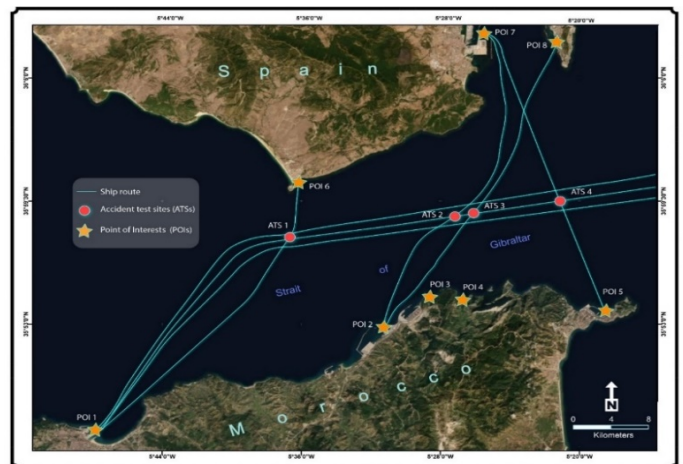


Figure 2: Locations of accident test sites (ATSS) and point of interests (POIs) used to evaluate the environmental risk in the proposed simulations.

### 4.1. Model application

In the proposed study, the yearly accident rate for the case study area, computed by eq. 3, is based on REMPEC data [69] related to accidents occurred in 42 years, from 1977 to 2019, in Western Mediterranean Sea. Thus, for the four ATSS  $i$ -th, considering the study area of about 653.245 km<sup>2</sup>, the accident rate is  $AR_i = 7.83 \times 10^{-06}$  accident/yr km<sup>2</sup>. The wind speed and wind directions

data have been collected by REMRO network database [83]. Those kinds of data related, as an example, to the ATS 1 appear in the table 5.

The consequence analysis has been carried out taking into consideration the following conditions:

- Three release sizes were defined: small (release <70 tons), medium (release between 70 and 7000 Ton) and large (release > 7000 Ton). Table 6 contains the  $P_s^{spill\ size}$  computed by eq. 4 according to accident data in the period 1977–2019.
- Twenty-four weather condition probabilities  $P_{i,h}^{weather}$ , associated to the h-th scenarios, in the four ATS i-th, have been used for the consequence modeling according to three wind speeds and eight wind directions combinations as follows:
  - $U_{wind} = 1.5\text{ m/s}, 14\text{ m/s}$  and  $24\text{ m/s}$ ;
  - 8 cardinal and intercardinal wind directions: north (N), northeast (NE), east (E), southeast (SE), south (S), southwest (SW), west (W), northwest (NW).

The probability of different atmospheric conditions, for  $U_{wind}=14\text{ m/s}$ , in the 4 different ATSs are listed in table 7. In the proposed simulations, the surface current in the four ATSs has been considered  $U_{current} = 0.6\text{ m/s}$  according to statistical data coming from [109, 110]. Concerning the horizontal diffusion coefficient,

the value  $D_h = 7\text{ m}^2/\text{sec}$  [88] has been adopted in the applications.

Table 8 indicates the oil spill probability  $P_{i,s,h}$  computed by eq.2 as the combination of the three different components in case of 700 Ton oil release category.

About 288 simulations have been carried out to evaluate the risk assessment on the sensible POIs on the African and European coasts. The simulations consist of 288 different scenarios related to three spill categories (70, 700 and 7000 tons), three different wind speeds (1.5, 14 and 24 m/s) in 8 wind directions in the four potential maritime accident locations (ATS1, ATS2, ATS3, ATS4).

For all simulations to observe the variations in the covered area, conditions such as wind velocity and current velocity are kept constant. The values have been input to generate spill location mappings over the period of time and are shown in the following figures.

The calculation of the axes of the oil slick spreading elliptical shape and related impacted area  $A_t$  computed by the model (5)-(14) for the three different release scenarios extended for a period of nine hours after the accident taken place (wind speed =14 m/s) is listed in table 9.

Table 4: The distances among the ATSs and the coastal POIs.

			Distance (km)			
			ATS 1 (35°57'06.5"N 5°37'04.2"W)	ATS 2 (35°58'11.7"N 5°28'00.8"W)	ATS 3 (35°58'22.5"N 5°26'30.2"W)	ATS 4 (35°59'03.9"N 5°20'44.8"W)
African coast	POI1	Tanger	24.56	36	38.5	46
	POI2	Port Tanger Med	12.42	9.19	10.46	17.22
	POI3	Dalia beach	13.84	7.25	8.13	14.78
	POI4	Oued Mersa beach	16.64	7.63	7.56	12.71
	POI5	Ceuta	28.86	16.78	15	11
European coast	POI6	Tarifa	6.34	12.87	14.77	23
	POI7	Algeciras	10	9.45	10.5	12.91
	POI8	Gibraltar	29.89	19	18	14

Table 5: Annual combined probability of wind direction and mean wind speed for ATS 1 (source: REMRO network database)

Direction	Average wind speed (m/s)									Total
	≤ 1.0	3.0	6.0	9.0	12.0	15.0	18.0	21.0	>21.0	
Calm	1.06E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.06E-02
N	0.00E+00	6.66E-03	1.16E-02	3.61E-03	2.80E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.21E-02
NNE	0.00E+00	6.43E-03	7.79E-03	1.15E-02	5.00E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.57E-02
NE	0.00E+00	6.20E-03	9.48E-03	1.22E-03	1.90E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.71E-02
ENE	0.00E+00	5.54E-03	1.95E-02	1.64E-02	6.71E-03	1.55E-03	5.00E-05	0.00E+00	0.00E+00	4.98E-02
E	0.00E+00	6.34E-03	3.73E-02	7.82E-02	8.41E-02	4.58E-02	1.57E-02	3.47E-03	0.00E+00	2.71E-01
ESE	0.00E+00	4.51E-03	1.53E-02	1.25E-02	5.54E-03	1.60E-03	3.80E-04	0.00E+00	0.00E+00	3.98E-02

SE	0.00E+00	3.99E-03	7.42E-03	1.64E-03	2.30E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.33E-02
SSE	0.00E+00	3.99E-03	5.49E-03	1.69E-03	4.70E-04	5.00E-05	0.00E+00	0.00E+00	0.00E+00	1.17E-02
S	0.00E+00	4.32E-03	8.78E-03	4.46E-03	1.55E-03	5.00E-05	9.00E-05	5.00E-05	0.00E+00	1.93E-02
SSW	0.00E+00	5.77E-03	1.20E-02	9.86E-03	6.34E-03	1.83E-03	9.40E-04	9.00E-05	0.00E+00	3.68E-02
SW	0.00E+00	8.40E-03	2.65E-02	1.49E-02	8.82E-03	4.51E-03	6.60E-04	9.00E-05	0.00E+00	6.39E-02
WSW	0.00E+00	1.20E-02	4.16E-02	1.84E-02	6.05E-03	2.86E-03	4.20E-04	0.00E+00	0.00E+00	8.13E-02
W	0.00E+00	1.37E-02	5.89E-02	3.17E-02	8.49E-03	1.97E-03	5.00E-05	1.90E-04	0.00E+00	1.15E-01
WNW	0.00E+00	1.35E-02	6.25E-02	2.82E-02	8.07E-03	1.69E-03	5.20E-04	0.00E+00	0.00E+00	1.14E-01
NW	0.00E+00	1.03E-02	4.22E-02	1.92E-02	5.12E-03	8.90E-04	5.00E-05	0.00E+00	0.00E+00	7.77E-02
NNW	0.00E+00	8.96E-03	2.22E-02	8.03E-03	1.31E-03	9.00E-05	0.00E+00	0.00E+00	0.00E+00	4.03E-02
Total	1.06E-02	1.21E-01	3.89E-01	2.61E-01	1.43E-01	6.29E-02	1.89E-02	3.89E-03	0.00E+00	1.0

Table 6:  $P_s^{spill\ size}$  computed according to the accident data in the period 1977-2019.

Spill category	Release size (Tons)	Number of accident	$P_s^{spill\ size}$
s=1	70	261	6.92E-01
s=2	700	72	1.91E-01
s=3	7000	44	1.17E-01

Table 7: Probability of different combinations of atmospheric conditions for wind speed =14 m/s in 8 different directions in each ATS.

Wind speed m/s	Direction	Accident Tests Sites			
		ATS 1	ATS 2	ATS 3	ATS 4
14	N	5.00E-03	5.00E-03	5.00E-03	5.00E-03
	NE	5.00E-03	5.00E-03	5.00E-03	5.00E-03
	E	2.10E-01	3.20E-02	3.20E-02	1.50E-02
	SE	5.00E-03	5.00E-03	5.00E-03	5.00E-03
	S	5.00E-03	5.00E-03	5.00E-03	5.00E-03
	SW	2.00E-02	1.25E-02	1.25E-02	1.20E-02
	W	7.00E-03	5.00E-03	5.00E-03	9.00E-03
	NW	5.00E-03	5.00E-03	5.00E-03	1.50E-02

Table 8: The probability  $P_{L,s,h}$  for oil spill release category s=2, 700 Tons, according to the 24 scenarios dictated by wind speed and direction combined probability.

Wind speed m/s	Direction	$P_{ATS\ 1}$	$P_{ATS\ 2}$	$P_{ATS\ 3}$	$P_{ATS\ 4}$
1,5	N	1.71E-07	3.88E-07	3.88E-07	2.84E-07
	NE	2.69E-07	2.09E-07	2.09E-07	5.98E-08
	E	1.34E-08	7.47E-09	7.47E-09	7.47E-09
	SE	2.09E-07	4.33E-07	4.33E-07	3.58E-07
	S	2.69E-07	5.83E-07	5.83E-07	2.84E-07
	SW	1.71E-07	2.84E-07	2.84E-07	2.39E-07
	W	2.99E-08	7.47E-09	7.47E-09	7.47E-09
	NW	1.10E-07	1.34E-07	1.34E-07	1.34E-07
14	N	7.47E-09	7.47E-09	7.47E-09	7.47E-09
	NE	7.47E-09	7.47E-09	7.47E-09	7.47E-09
	E	3.14E-07	4.78E-08	4.78E-08	2.24E-08
	SE	7.47E-09	7.47E-09	7.47E-09	7.47E-09
	S	7.47E-09	7.47E-09	7.47E-09	7.47E-09
	SW	2.99E-08	1.86E-08	1.86E-08	1.79E-08
	W	1.04E-08	7.47E-09	7.47E-09	1.34E-08
	NW	7.47E-09	7.47E-09	7.47E-09	2.24E-08



24	N	7.47E-09	7.47E-09	7.47E-09	7.47E-09
	NE	7.47E-09	7.47E-09	7.47E-09	7.47E-09
	E	7.47E-09	7.47E-09	7.47E-09	7.47E-09
	SE	7.47E-09	7.47E-09	7.47E-09	7.47E-09
	S	7.47E-09	7.47E-09	7.47E-09	7.47E-09
	SW	7.47E-09	7.47E-09	7.47E-09	7.47E-09
	W	7.47E-09	7.47E-09	7.47E-09	7.47E-09
	NW	7.47E-09	7.47E-09	7.47E-09	2.24E-08

Table 9: The computation of the elliptical spreading area  $A_t$  for the oil slick during 9 hours after the incident occurred.

Wind speed (m/s)	Release size (Tons)	Time (hours)	$A_t$ (km <sup>2</sup> )	$Q_t$ (m)	$R_t$ (m)
14	70	1	0.41	625.72	2354.85
		2	0.65	744.11	3652.15
		3	0.85	823.49	4765.06
		4	1.04	884.90	5775.62
		5	1.22	935.67	6717.37
		6	1.40	979.30	7608.20
		7	1.56	1017.78	8459.13
		8	1.73	1052.33	9277.51
		9	1.89	1083.78	10068.61
	700	1	1.53	1346.36	3075.49
		2	2.23	1601.10	4509.14
		3	2.79	1771.91	5713.48
		4	3.28	1904.04	6794.76
		5	3.72	2013.28	7794.98
		6	4.13	2107.17	8736.07
		7	4.52	2189.96	9631.31
		8	4.88	2264.30	10489.48
		9	5.23	2331.97	11316.80
	7000	1	6.71	2900.03	4629.16
		2	9.56	3448.74	6356.78
		3	11.76	3816.66	7758.23
		4	13.64	4101.27	8991.99
		5	15.31	4336.56	10118.26
		6	16.82	4538.80	11167.70
		7	18.23	4717.13	12158.47
		8	19.54	4877.26	13102.44
		9	20.78	5023.01	14007.84

Table 10: Time (hours) required by the oil slick to reach the POIs on the Moroccan coastline for accidents occurred in one of the ATs according to different scenarios.

			Release quantity									
			70 Ton			700 Ton			7000 Ton			
Wind speed [m/s]			1.5	14	24	1.5	14	24	1.5	14	24	
AFRICAN PART	Time (hour)	Tanger	ATS 1	12	4.5	2.5	8	3.5	2.5	4.5	2.5	1.5
			ATS 2	17.5	5.5	4	12	5	3.5	7	4	3
			ATS 3	18.5	6	4	12.5	5.5	3.5	7.5	4.5	3
			ATS 4	21	7	4.5	15	6.5	4.5	8.5	5	3.5
		Port Tanger Med	ATS 1	6	2	1	3.5	1.5	<1	2	1	<1
			ATS 2	4	1	<1	2	1	<1	1	<1	<1
			ATS 3	4.5	1.5	<1	2.5	1	<1	1	<1	<1
			ATS 4	9	3	1.5	5.5	2.5	1.5	3	1.5	1
		Dalia beach	ATS 1	6.5	2	1	4	1.5	1	2	1	<1
			ATS 2	2	<1	<1	1	<1	<1	<1	<1	<1
			ATS 3	2.5	<1	<1	1.5	<1	<1	<1	<1	<1
			ATS 4	7	2	1.5	4.5	2	1	2	1.5	<1

	Oued Mersa beach	ATS 1	8.5	2.5	1.5	5	2.5	1.5	3	1.5	1
		ATS 2	2	<1	<1	1	<1	<1	<1	<1	<1
		ATS 3	2	<1	<1	1	<1	<1	<1	<1	<1
		ATS 4	6	2	1	3.5	1.5	<1	2	1	<1
	Ceuta	ATS 1	14.5	4.5	3	9.5	4	2.5	5.5	3.5	2.5
		ATS 2	8	3	1.5	5	2.5	1.5	3	1.5	1
		ATS 3	7.5	2.5	1.5	4.5	2	1.5	2.5	1.5	<1
		ATS 4	5	1.5	<1	3	1	<1	1.5	<1	<1

Table 11: Time (hours) required by the oil slick to reach the POIs on the European coastline for accidents occurred in one of the ATs according to different scenarios.

			Release quantity									
			70 T			700 T			7000T			
Wind speed [m/s]			1.5	14	24	1.5	14	24	1.5	14	24	
EUROPEAN PART	Time (hour)	Tarifa	ATS 1	1	<1	<1	1	<1	<1	<1	<1	<1
			ATS 2	6	2	1	3.5	1.5	<1	2	1	<1
			ATS 3	7	2.5	1.5	4.5	1.5	1	2	1.5	<1
			ATS 4	12	4	2.5	7.5	3.5	2.5	4.5	2.5	1.5
		Algeciras	ATS 1	4.5	1	<1	2	1	<1	1	<1	<1
			ATS 2	4	1	<1	2	1	<1	1	<1	<1
			ATS 3	4.5	1	<1	2.5	1	<1	1	<1	<1
			ATS 4	6	2	1	3.5	1.5	<1	2	1	<1
		Gibraltar	ATS 1	14.5	5	3	9.5	4.5	2.5	5.5	3.5	2.5
			ATS 2	10	3.5	1.5	6	2.5	1.5	3.5	2.5	1.5
			ATS 3	9.5	3.5	1.5	5.5	2.5	1.5	3.5	2	1.5
			ATS 4	7	2.5	1.5	4.5	2	1	2.5	1.5	<1

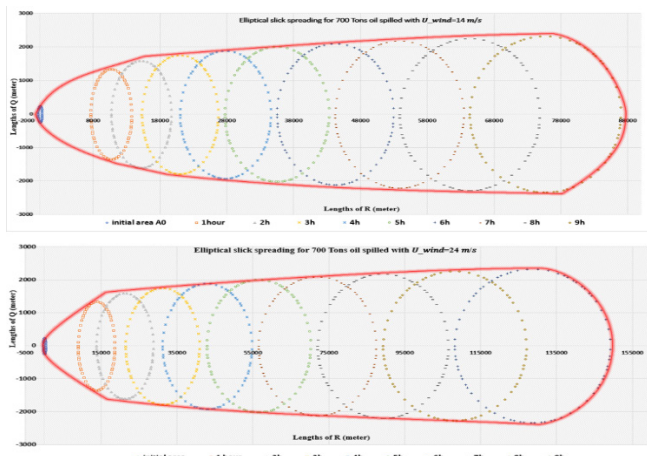


Figure 3: Elliptical slick spreading for 700 Tons oil spilled with  $U_{wind} = 14 \text{ m/s}$  and  $24 \text{ m/s}$ .

The plots show a series of elliptical shapes for the different scenarios that were interpreted according to the resulting vector of the wind-to-current vector interaction. Figure 3 and Figure 4 shows the applications of the consequence model to simulate the oil slick spreading and trajectory prediction in relation to different meteorological conditions. Specifically, Figure 3 shows the related graphical interpretation of the oil slick spreading for 700 Ton of spilled oil for different conditions of wind speed ( $U_{wind}=14\text{m/s}$  and  $24\text{m/s}$ ), which represents the development of

the oil spill area and movements according to the time in the wind direction since the origin. The main one is that the elliptical shape is moving significant distances from the origin. This is explained by having the factor applied to the wind and current vectors being too large.

Figure 4 represents the visualization, by a GIS, of the simulated scenario which concerns a maritime spill accident, occurred in the ATS4, with an estimated spill release of 700 tons, with  $U_{wind}=14 \text{ m/s}$  and major wind direction from Northeast-East (NE), which is estimated to impact the coast at POI1 within 6 hours of the accident release in ATS4.

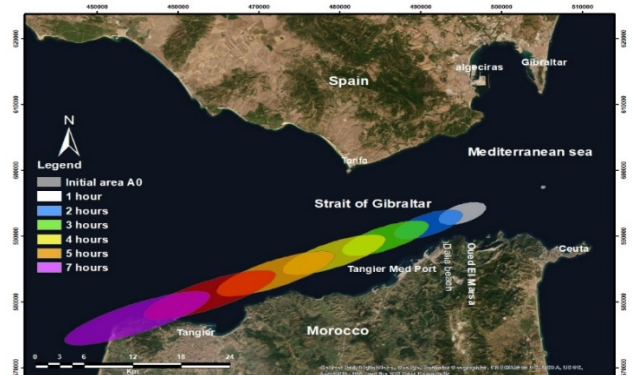


Figure 4: Estimated Spill location for 700 Tons from ATS 4 with wind speed  $14 \text{ m/s}$  (wind direction: Northeast-East).

## 5. Risk model application

In order to evaluate the environmental risk due to coastal pollution occurring in the event of a spill accident, it is necessary to identify risk's levels. In the proposed model, the potential environmental risk was assessed on the basis of the time required by the oil slick to reach the European and African coasts assuming that an oil spill accident may have occurred in one of the ATSSs.

The proposed Lagrangian-based maritime and coastal risk model can be used not merely in oil spill response and contingency planning but also in assessing risk impact. In the event of an oil spill, by a limited set of necessary meteorological data, the predictions of the slick movements and trajectories may be provided to the competent authorities. The main result of the proposed approach is the possibility to define a risk ranking for the coastal area based on the forecasted slick movements and to determine, under specified meteorological conditions, the time required by the oil slick to hit the littoral.

Tables 10 and 11 represent the estimated times (in hours) required by the oil spill to reach the POIs in the African and European coasts coming from the different ATSSs off the Strait of Gibraltar according to different scenarios.

The oil spill risk assessment is defined considering the cumulative probability, related to the overall simulated scenarios, that the oil slicks reach the coastal POIs in the successive hour time slots after the beginning of the oil spill accident releases.

Figures 5 and 6 represent, respectively, the coastal environmental risk for the selected African and European POIs. Among the selected POIs, Oued Mersa and Dalia represent the first locations to be affected in case of accidents in the Strait of Gibraltar in the first two hours. Besides, the region of Tarifa and Algeciras also appears to be subjected to a relevant risk on the European side.

According to the timing, after 4 hours, Port Tangier Med and the beaches of Oued Mersa and Dalia beach, on the African Mediterranean coast, have the main probability to be hit by an oil slick generated by maritime accidents in the study area. On the European side, the risk probability of oil beaching on the coasts, is growing, respectively, for Algeciras, Tarifa and Gibraltar.

Due to the interaction between the wind flow and the geography of the coast, the Gibraltar strait is very windy. It is exposed mainly to two types of winds [111,112]:

- East winds dominate in March, and from July to October, with a wind speed exceeding 8 m/s is 22% of the days;
- The west winds of Atlantic origin and important source of humidity and precipitation, dominate from December to April [111–113].

According to data provided by REMRO Network [83], the wind in the test points ATS1 and ATS4 has direction East-South-East and West direction (ESE-W) with a percentage of 53%, directed to European side, and direction West-North-West and East direction (WNW-E) in 47%. On the other hand, for the test points ATS2 and ATS3, the direction of the dominant winds, towards the Moroccan coast, is between WNW-E with a percentage of 61% (39% for ESE-W).

The importance of the proposed model appears to be most obvious due to this wind variability. Thus, it represents an added value in the real time applications in case of maritime accidents.

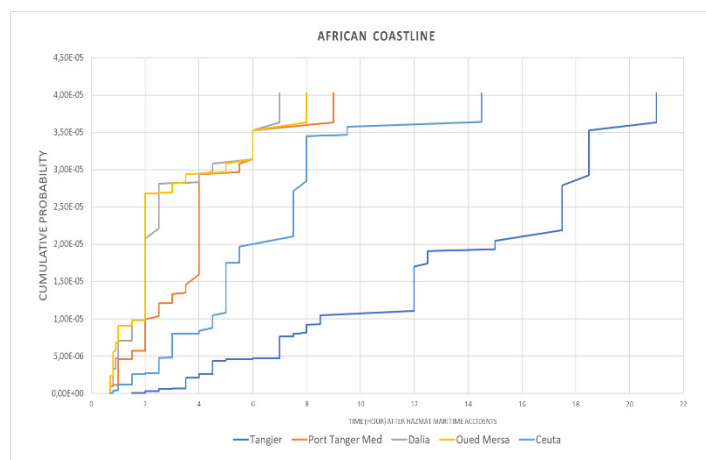


Figure 5: Risk evaluation on the African POIs

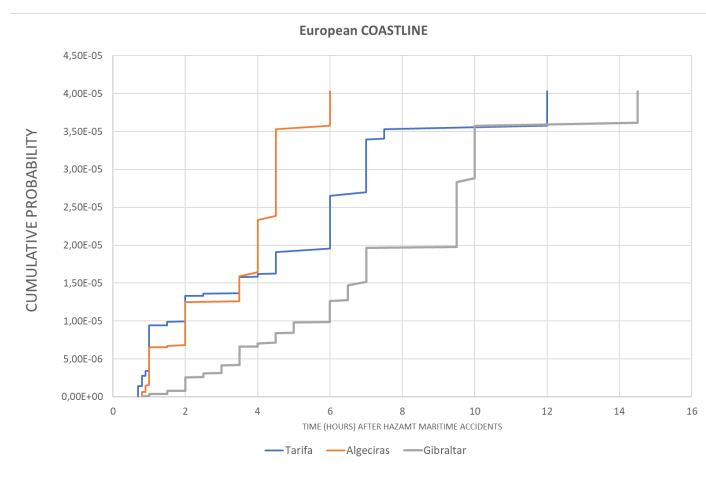


Figure 6: Risk evaluation on the European POIs.

## 6. Conclusion

The proposed risk model provides wide-ranging and fast information on the direction, spreading and magnitude of the oil spill, as well as it identifies the coastal areas which may be affected more or less quickly. This approach may be integrated with a GIS tool to generate detailed simulated maps on trajectories and oil slick spreading toward the relevant coasts.

The proposed approach presents a reliable methodology to classify the risk in marine and coastal areas due to the maritime transport of dangerous goods. The main contribution of our method is based on an integration of the probability of the maritime accident in each specific area and the related accident consequences, and, besides, it uses a simple 2D consequence model instead a more complicated 3D model. In the current literature, in fact, the mainly works focused on the movements of the oil slick and its impact without taking into account the accident probability.

The proposed model has been applied to 288 significant scenarios generated considering four potential accident sites in the West Mediterranean Sea. The accident probability analysis is function

of three components related to maritime oil spill accident frequency on the maritime routes included in the study area, probability of spill sizes, and a joint probability function of wind direction and speed. The consequences model related to the prediction of the oil slick trajectories and affected areas takes into consideration the spreading, the advection and the diffusion processes. To determine the oil spill path, data about the weather conditions and surface currents have been utilized.

Risk assessment for the coastal POIs is based on the cumulative probability to be impacted by an oil spill, over the time, starting from the initial accident event.

The main contribution of this paper is twofold. Firstly, the model application ranks the coastal locations according to higher hazmat risk to be strongly affected by the oil spill in each time intervals. Secondly, the proposed model, being connected to adequate ICT equipment to acquire in real time data on weather and sea currents, represents a useful tool to manage the immediate containment and recovery activities.

However, the validation test of the model in the framework of the Saint-Tropez (France) spill incident verified that the model algorithms provided an encouraging level of accuracy. Further developments have been identified to improve the accuracy and functionality of our model.

However, the proposed model may underestimate the oil slick impact area since it does not encompass all the possible physical processes in the water column. In the future development of the model, also dispersion, emulsification and dissolution phases may be taken into account.

Anyway, the main purpose of our work is to realize a simplified method useful for the public authorities which have quickly to intervene in case of accident.

The introduction of new parameters and variables in the model surely may provide the users with a more reliable prediction of the oil slick movements but also, they may complicate the applicability of the approach in case of accident, fast recovery after incidents, mitigation of consequences. In addition, accurate information on the environment such as spatially and temporally varying wind, water current and wave fields are essential for a reliable prediction of the transport and fate of the oil slick. This model currently has limited capability to incorporate operational predictions of wave impact. As a result, the model is unable to simulate the subsurface transport of dispersed oil droplets related to vertical dispersion due to wave action. The possibility to incorporate the underwater oil transport functionality will be explored in future improvements of the modeling system.

#### Conflict of Interest

The authors declare no conflict of interest.

#### Acknowledgment

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