Development of an oil spill hazard scenarios database for risk assessment

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ABSTRACT

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The occurrence of oil spills in coastal regions may have catastrophic consequences on the environment and severe socio-economic impacts. This work presents a new methodology to evaluate the risk associated with oil spills in coastal zones and estuaries, and illustrates its application in a coastal lagoon (Ria de Aveiro, Portugal). A ranked list of the hydrodynamic scenarios under which oil spills are most likely generated through the analysis of 33 years of wave and wind data, retrieved from the ERA-INTERIM project database, and from the analysis of oil spills that occurred in the Atlantic Iberian shelf. Considering six spill locations and a single oil type spill inside the Aveiro harbor, the database resulted in approximately 3500 simulations. Hydrodynamic simulations were made with the MORSYS2D modeling system, a soft coupling of the hydrodynamic model ELCIRC and the wave model SWAN. The high-accuracy, unstructured grid, oil fate model VOILS was used in 2D mode to simulate the transport and the oil weathering processes at the surface and in the intertidal areas. The hazard assessment analysis included the determination of the trajectory of the plumes, the shoreline retention areas affected by the oil and their oil exposure time. Time evolution of the oil properties, such as the oil evaporation rate and emulsification processes of the mixture, are provided to support clean-up operations, as well as robustness controls such as oil mass balance.

ADDITIONAL INDEX WORDS: *climatology, oil spill modeling, risk assessment.*

INTRODUCTION

Near shore and offshore oil spill events have huge social, economic and environmental impacts, which can ultimately cripple an entire coastal area for long periods of time, as recent examples demonstrate – Deep Sea Horizon in the Gulf of Mexico (Mackowsky *et al.* 2010), Prestige in the bay of Biscay (Albaigés *et al.* 2006) and Cercal in Northern Portugal (Costa *et al.* 2012). Simultaneously, adequate preparedness of harbor and maritime authorities to potential oil spills requires significant material and human resources. Hence, risk assessment studies can bring enormous benefits, by optimizing emergency resource allocation.

The development of hazard maps for oil spills constitutes a first step towards the generation of risk maps. These hazard maps should provide detailed indications on the areas which will most likely be affected by an oil spill in a given region, together with the associated probability. Such maps can be used for both long-term planning (i.e., before the occurrence of an accident) and immediate response action (i.e., once the accident occurs).

Hence, the generation of these maps from existing information should be rapid so they can be updated as new information becomes available. For instance, a map developed for planning purposes has to rely on educated guesses on where the spill is more likely to occur. In contrast, once the accident does occur, the map can be updated to take into account the location of the spill or other information. Maps for specific conditions can also be useful. For instance, hazard maps for specific seasons can be used in the risk analyses, since the vulnerability can also vary seasonally.

The present paper describes a new methodology to develop hazard maps of oil spills in coastal regions, and illustrates its application in a coastal lagoon. The approach uses historical information on previous spills to restrict the range of environmental conditions associated with the accidents, as well as the combined probabilities of different environmental conditions (tides, waves and wind). A database of simulations of both hydrodynamics conditions and oil slick transport and weathering is then built, providing the building blocks for the hazard maps.

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The paper starts by presenting the case study (the Aveiro lagoon in Northern Portugal). The new method is then described in detail, from the analysis of past accident records to the generation of the simulation database and the numerical models used in the study. Finally, the hazard maps are presented.

STUDY AREA

The present study was focused on the Ria de Aveiro (**Error! Reference source not found.**), a complex lagoon system located on the western Portuguese coast (40.38ºN, 8.45ºW), spanning 45 km long and 10 km wide. This shallow system is mainly formed by four channels (Mira, Ílhavo, Espinheiro and S. Jacinto). The lagoon has freshwater inputs from five distinct rivers, but the circulation is mainly controlled by tides (Dias *et al*., 2000; Lopes *et al.* 2005). Outside the inlet, wave-driven currents can be significant, since the wave climate is very energetic (Plecha *et al.*, 2012).

The Aveiro lagoon has many, and sometimes conflicting, uses such as harbor activities, industry, agriculture, fishery, aquaculture, tourism and nautical. Also, due to its rich biodiversity and fragile ecosystems, this region is highly vulnerable to oil spills events (Mendes *et al*., 2009). The significant oil spill hazards associated to the presence of a large commercial harbor in the inner lagoon motivate the development of mitigation measures and risk assessment studies.

METHODOLOGY

General Approach

The present work aims at developing a methodology to build hazard scenarios databases. The methodology is illustrated for the region of the Aveiro lagoon. The oil spill hazard database consists of results from oil spill model simulations and their associated probabilities. The specification of the simulation conditions and the determination of the probabilities are based on the climatological conditions of the study region, historical records of past oil spill events and expert judgment on the most likely locations for the occurrence of an oil spill in a particular port or coastal region. The methodology can be divided in four tasks:

1. Past oil spill occurrences are analyzed to determine the most favorable weather and ocean conditions for this type of event in the study area.
2. The climatological conditions for the region of interest are determined for wind, waves and tides. This analysis is performed from databases of past environmental conditions in the region (from hincasts or measured data), constrained with the information determined in the first task. This task defines the climatological conditions propitious to the occurrence of spill accidents and their associated probabilities.
3. A numerical modeling system is used to generate a hydrodynamic database for the scenarios defined in the previous task. If computational costs are a limiting factor, the probabilities associated with each scenario can be used to restrict the simulations to the most likely conditions.
4. Finally, the hazard scenarios database is built using an oil spill model. For each of the hydrodynamic simulations included in the previous database, several oil spill simulations are performed considering the most likely locations, as well as different release times in the tidal cycle. The probability associated with each location is estimated from expert judgment, based on port activities.

Ultimately, the analysis of the final hazard scenarios database provides the information needed for the production of the hazard probability maps. The following sections explain in more detail each of these tasks.

Accident Threshold Conditions

In order to define the weather conditions most prone for the occurrence of accidental oil spills along the Portuguese coast, all historical spill records were analyzed. Information was retrieved from CEDRE (Centre of Documentation, Research and Experimentation on Accidental Water Pollution – http://www.cedre.fr/en/spill/alphabetical-classification.php) and DGAM (Direção Geral da Autoridade Marítima) databases, which included 35 ship accidents that occurred along the Iberian Atlantic shelf between 32º- 46º N and 0º- 40ºW (Figure 2).

The historical data was useful for identifying the frequency of these types of accidents and with weather and ocean conditions most favorable for their occurrence.

The monthly probability of occurrence of oil spill accidents in this region (Table 1) shows that ship accidents are most frequent

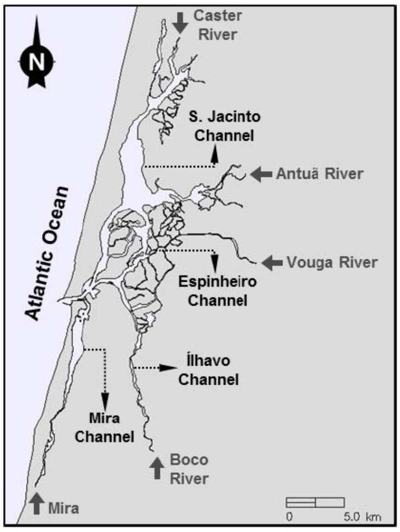

Figure 1: Aveiro's lagoon geography.

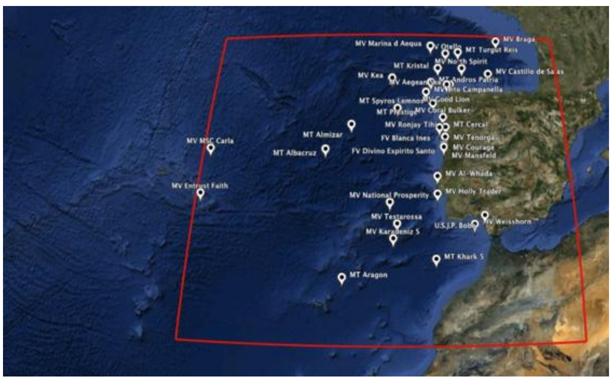

Figure 2: Location of the 35 ship accidents involving oil leakages in the Iberian Atlantic region. Each marker corresponds to an accident.

in the wintertime. Therefore, for oceanographic standardization purposes, the DJF period was selected as the study period. Together, these three months represent about two thirds of the oil spill occurrences in the region.

Table 1: Probability of occurrence of the 35 registered accidents in the region. No accidents are reported between April and September.

	Jan	Feb	Mar	Oct	Nov	Dec
Prob. (%)	21.2	6.1	9.1	12.1	15.1	36.4

The NCEP-GDAL and ERA-I global reanalysis project databases were selected to determine the weather and ocean conditions for the period defined due to their long-term series and availability. Wind speed, wind direction and significant wave height (Hs) were analyzed, as they are the variables with the greatest influence on sea navigation conditions.

A comparison between time series of wind and waves for all locations of the 35 historical spills show significant correlations between them. Wind and waves are highly correlated, in both magnitude and direction (Figure 3, Table 2).

Table 2: Correlation coefficients between wind speed and significant wave height (Magnitude Correlation), and between wind and wave direction (Direction Correlation).

Datasets	ERA-1	NCEP
Direction Correlation	0.53	0.54
Magnitude Correlation	0.86	0.71

Only the magnitudes of wind speed and significant wave height were used in the definition of the accident threshold values. The analysis of the wind and wave conditions at the time of the accidents (Figure 4) provided the thresholds for the occurrence of ship accidents. These thresholds were defined from the analysis of the ERA-I reanalysis dataset due to the existence of several outliers in the NCEP wave set. The thresholds were calculated following different criteria for wind and wave data. The minimum wind speed in the dataset was 3.9 m/s. Hence, a value of 3.0 m/s was specified as the threshold below which no accidents are expected to occur. The wave threshold was specified as the lowest value in which ocean conditions are believed to be responsible for the accidents. This criterion was adopted because several accidents in the dataset, with wave heights lower than 4 m, were not due to the wave or wind conditions, but to other causes (e.g., engine failure, fires). Based on these data, threshold values of 3.0 m/s for wind speed and 4.0 m for Hs were specified.

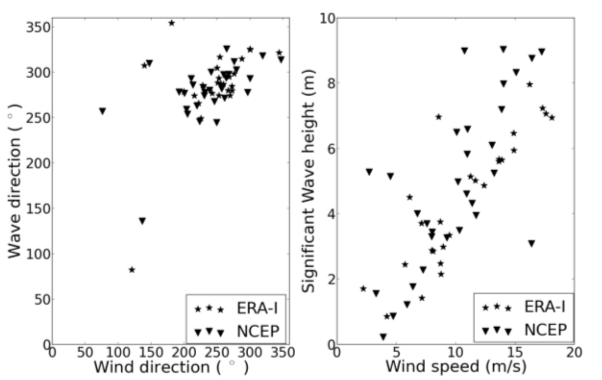

Figure 3: Comparison between the direction (left) and magnitude (right) of wind and waves, for NCEP and ERA-I reanalyses.

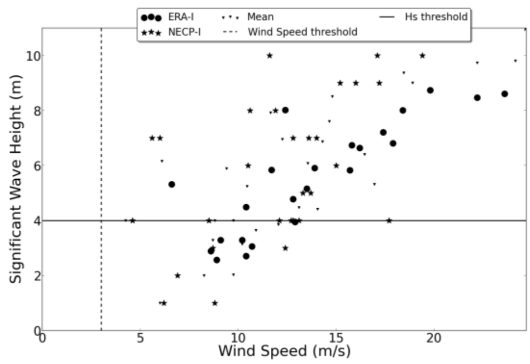

Figure 4: Accident retrieved values for wind speed and wave significant height from multiple data sources.

Climatological Analysis

The climatology of winds and waves was characterized based on the time series of the grid point, of the Era-Interim database, nearest the Aveiro lagoon and located at 40º31'N / 8º58'60.00"W. The global dataset is characterized by a time span of 33 years (1979-2012), with a temporal resolution of 6 hours and a spatial resolution of 1.5º. The variables considered in the climatological analysis were zonal and meridional wind components, combined significant wave height and swell, mean wave period and mean wave direction. From here on the combined dataset will be named simply significant wave height. Figure 5 and Figure 6 show the monthly means and their standard deviations as well as the minimum and maximum values and their comparison with the accident threshold values determined previously.

Both figures show a seasonal pattern, with lower (higher) standard deviations during summer (winter). The mean and median values of Hs are below the threshold value, although maximum values are above this level (Figure 5). In contrast, both mean and median wind magnitudes are above the wind speed threshold (Figure 6). This analysis shows that the Aveiro lagoon is climatologically prone to possible oil spill events caused by adverse atmospheric and ocean conditions.

Hazard scenarios database setup

The generation of a scenarios database involved the definition of the environmental conditions and their associated probabilities. Environmental conditions are defined herein as a set of values for 5 variables: wind speed and direction, significant wave height, mean wave direction and mean wave period. A subset of time series of these values for the winter months alone (December-February) was retrieved from the ERA-Interim database. This subset was further reduced by eliminating the elements of the set in which the wind speed or the significant wave height were smaller than the corresponding thresholds defined above. The continuum range of each of these

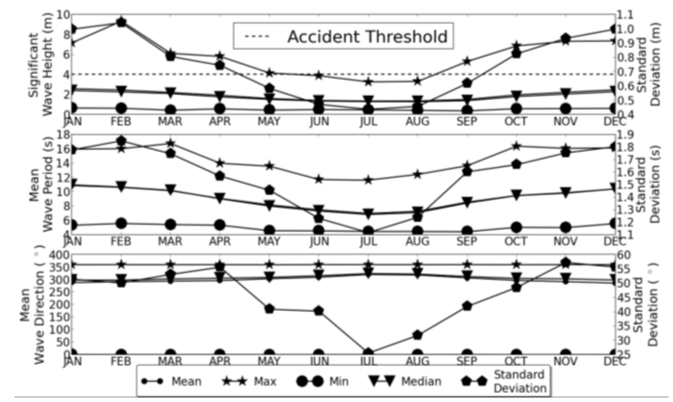

Figure 5: Monthly statistics for wave-related variables.

5 variables was then discretized into three intervals, limited by the 0th, 75th, 95th and 100th percentiles.

The choice of these limits was guided by the need to provide a higher refinement for the most extreme situations. The probability associated with each 5-dimensional bin was then calculated for the winter months, and the bins were ranked according to this probability.

Finally, a representative value for each of the five variables was determined for each bin, together with a standard deviation representative of the bin. The representative value is taken as the average of all the elements of the subset in the bin (Figure 7). The limits of the various bins and the standard deviations are represented in Table 4.

The total number of environmental conditions to consider in the simulations was further reduced to 64 by eliminating all bins that did not include any occurrence. Since this methodology was only applied to the wind and wave variables, the information regarding the tides was added *a posteriori*. Three tidal amplitudes were considered: spring tide, neap tide and mean tide. The final number of hydrodynamic simulations was set to 192. The parameterization from Table 4 was used to establish the hydrodynamic scenarios which feed the oil spill simulations.

Regarding the oil spill simulations and based on port activities and concerns, six locations were chosen as the most probable areas for the occurrence of an oil spill in the lagoon (Figure 8).

The oil spill simulations were started on three distinct tidal phases: high tide, low tide and maximum flood. Maximum ebb was not considered since tidal ebb currents are very strong and consequently most of the oil would leave the lagoon soon after the spill, thereby minimizing the hazard. The final hazard scenarios database, which accounts for the hydrodynamic and oil spills setups, is constituted by 3456 simulations (192 hydrodynamic simulations × 6 spill locations × 3 tidal phases).

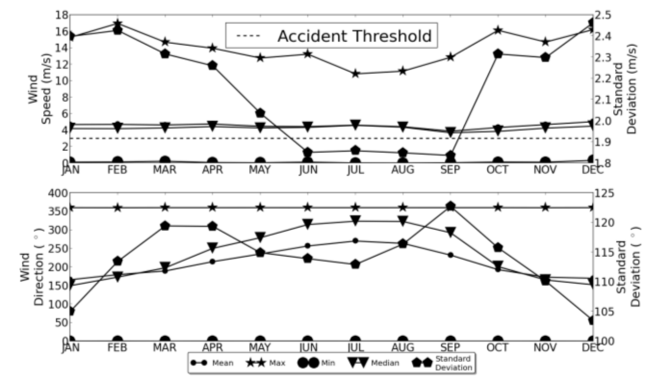

Figure 6: Monthly statistics for wind-related variables

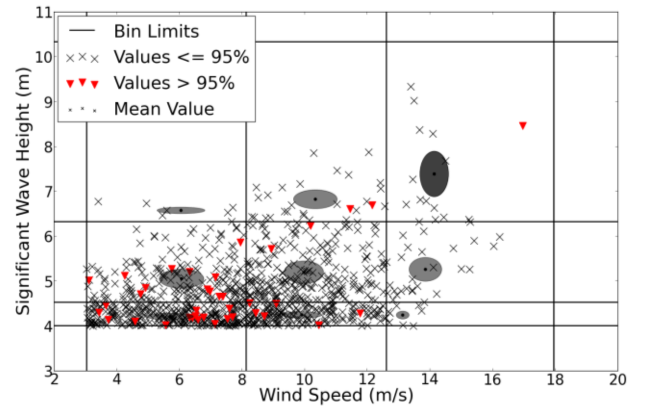

Figure 7: Wind speed vs. Hs bin constraints, representative values and error ellipses, for data above the thresholds.

Table 3: Representative values for each parameterized class (Mean,Standard deviation).

	frequent cases Percentiles (0th -75th) ($\mu \pm \sigma$)	mildly observed cases Percentiles (75th -95th) ($\mu \pm \sigma$)	less frequent cases Percentiles (95th -100th) ($\mu \pm \sigma$)
Mean wave direction (º)	275.5±1.5	303.9±1.4	333.6±1.3
Wind direction (º)	194.4±11.1	295.1±4.4	351.1±0.2
Significant wave height (m)	4.2±0.02	5.2±0.1	6.9±0.3
Wind speed (m/s)	5.9±0.2	10.1±0.2	13.7±0.4
Mean wave period (s)	11.3±0.4	13.4±0.1	15.2±0.1

Numerical models

Two modeling systems were used in this study: MORSYS2D and VOILS. MORSYS2D (Bertin *et al.*, 2009) consists of (1) a wave propagation model (SWAN, Booij *et al.*, 1999), (2) a circulation model (ELCIRC, Zhang *et al*., 2004) and (3) a sand transport and bathymetry update model (SAND2D, Fortunato and Oliveira, 2004, 2007), sharing information and interacting through Perl scripts. This platform simulates morphological evolution under the combined action of tides, waves, freshwater discharge and wind. However, the bathymetry was fixed in the present study, and the sand transport model was not used. Therefore, all hydrodynamic simulations were made with the coupled system using ELCIRC and SWAN. VOILS (Azevedo *et al*. 2009, 2014; Azevedo, 2010) is an oil spill model, based on a Eulerian-Lagrangian approach to solve the transport equation and uses unstructured horizontal grids for domain representation. VOILS can be used in two distinct modes: a 2D

Figure 8: Location of the six predefined oil spills..

surface model, which was used herein, and a 3D mode, that results from the hard-coupling of the transport and transformation model with the hydrodynamic model SELFE (Zhang and Baptista, 2008), where the transport of the oil in the water column is calculated.

In both modes the model simulates the major transformation processes: evaporation, emulsification, spreading, dispersion, dissolution, and shoreline retention and reposition. Each process can be switched on and off, and solved with different formulations.

The information retrieved from the climatological analysis was used to setup the hydrodynamic simulations. The hydrodynamic simulations were forced with 12 tidal constituents (Z0, MSF, O1, K1, N2, M2, S2, MN4, M4, MS4, M6 and 2MS6), taken from the regional model of Fortunato *et al.* (2002). The simulation grid for the hydrodynamic and the oil spill models had about 70000 elements and 42000 nodes. The validation and calibration of MORSYS2D in the Aveiro lagoon is described in Vaz *et al.* (2013). The time steps were set to 90 s and 900 s in the hydrodynamic and oil spill runs, respectively.

Hazard probability maps

The analysis of the hazard scenarios database provided useful information regarding the study region. One of the products developed is the hazard probability map (*Hp*) that was determined using the expression (1):

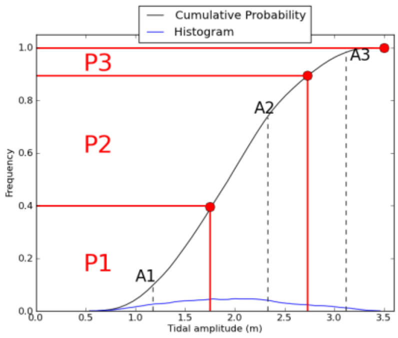

Figure 9: Histogram of tidal ranges at the Aveiro inlet, from a 19 years tidal synthesis. (A1, A2, A3) = (1.16, 2.33, 3.12) m correspond to the mean tidal amplitudes used in the scenarios simulations for each tidal range. Their associated probabilities of occurrence are (P1, P2, P3) = (40.7%, 48.7%, 10.6%), corresponding to neap, mean and spring tide, respectively.

$$Hp(x,y) = \sum_{i=1}^{n} P_i \sum_{j=1}^{m} \sum_{k=1}^{l} S_j T_k Q(x,y)_{ijk} / \sum_{i=1}^{n} P_i \quad (1)$$

where, *Hp* is the hazard probability map (Figure 9), *n* is the number of hydrodynamic simulations used in the analysis, *m*=6 is the number of spill locations, P_i is the occurrence probability associated to the hydrodynamic simulation, S_j is the occurrence probability associated to spill location *j*. $Q(x,y)_{ijk}$ is an imdicator of the presence of oil at each node of the grid: *Q* is 1 if oil reached the point (*x*,*y*) during the simulation, and 0 otherwise. T_k is the probability associated to the tidal range of the simulation (neap, mean or spring tide), and *l*=3 is the number of tidal ranges considered (Figure 9). The scaling by the sum of the probabilities in Eq. (1) allows estimating the hazard from a limited number of simulations.

Figure 10 shows the hazard probability maps for the first 20 simulations, which correspond, approximately, to the 40% most probable hydrodynamic conditions for the occurrence of an oil spill. Figure 10 shows the probability of a particular point in the Aveiro lagoon domain to be contaminated with oil, from a spill located in Barra (Figure 10a) and Terminal Sul (Figure 10b). The probability of a spill occurring in Barra or in Terminal Sul was estimated with the collaboration of the harbor authorities as approximately 35% and 5%, respectively. Because these maps were built considering only the 20 most probable hydrodynamic conditions and the maximum values found were 26.25%, in Barra and nearly 3.75% in Terminal Sul.

The hazard probability maps can be used by port administration to predict which areas of the lagoon are most likely to be affected, and make an effective management of the logistic capabilities and response strategies to mitigate oil spill events inside the Aveiro lagoon.

In the future, these hazard probability maps will be confronted with the vulnerability maps for the Aveiro lagoon region, to establish the high-resolution risk maps for this coastal domain.

CONCLUSIONS

The approach presented herein allows the generation of hazard maps for oil spill accidents in coastal regions. The information required is now widely available worldwide: oil spill accidents (CEDRE-http://www.cedre.fr/en/spill/alphabetical-classification.php), hindcasts of weather and ocean conditions (ERA-I), and tidal constituents from tide gauges or numerical models. The association of probabilities to each environmental scenario has several advantages: 1) it opens the route to quantitative and rigorous risk analyses, which are critical for decisions on resource allocation; 2) it provides simple criteria to decide which simulations to perform, since the most likely scenarios are also those that affect the results the most; and 3) it provides a simple and rigorous way to generate new maps by including additional information. The maps generated herein are made available to the decision-makers through a WebGIS platform for both oil forecast and risk analysis, which allows their combination with vulnerability information (Oliveira et al., this issue).

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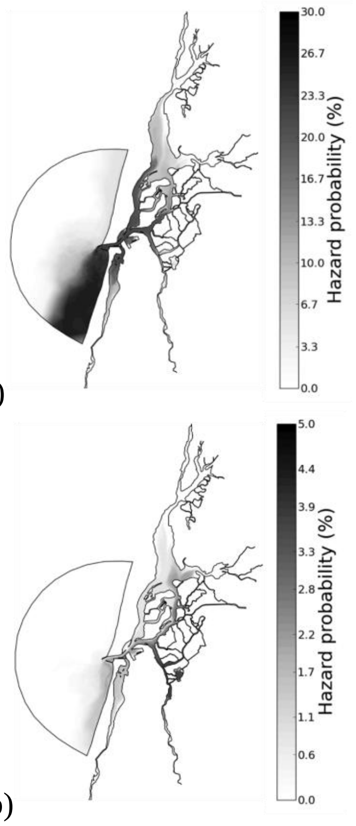

a)

b)

Figure 10: Hazard probability maps for the 20 most probable scenarios (approximately 40% of the total hazard scenarios dataset). a) oil spill in Barra and b) oil spill in Terminal Sul.

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