

## INTEGRATED STOCHASTIC MODELING FOR QUANTITATIVE ECOLOGICAL RISK ASSESSMENT OF POTENTIAL OIL SPILLS IN A MARINE ECOSYSTEM AT NORTHEASTERN BRAZIL

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### ABSTRACT

These same authors published in the SBPO 2011 a methodology for quantifying ecological risks (i.e. risks to plants and animals) of industrial accidents, which emerged from the need for definitive procedures to assess ecorisks related to rare events. We present, in a preliminary form, an application of this methodology by building an integrated model to underpin a quantitative ecological risk assessment for potential accidental spills in the activities of oil ship transportation to supply the Suape Port and Industrial Complex at Northeastern Brazil. The critical accidental scenarios of an oil spill were simulated, their frequencies of occurrence were estimated via reliability analysis, and the ecosystem exposure was predicted via fate and transport modeling. Predicted exposure was used as input to a stochastic ecological model that predicts the added risk of extinction to a native fish population used as environmental bioindicator. Ecorisks were quantified at population-level, categorized, and evaluated.

**KEY-WORDS.** Quantitative risk assessment; Ecological risk assessment; Oil spill.

**Main area:** OR in Oil & Gas; Probabilistic Models; OR in Agriculture and Environment.

## 1. Introduction

Recent industrial accidents such as toxic spills have been causing catastrophic damage to local ecosystems (i.e. plants and animals) and consequently great financial losses to the accountable operators. For instance, the British Petroleum spill (Gulf of Mexico, 2011), the wrecks of the oil tankers Prestige (Spain, 2002) and Erika (France, 1999), and the chemical spills at Doñana (Spain, 1998) and Baia Mare (Romania, 2000) (EEA, 2003). Furthermore, a high number of less harmful (but not negligible) accidents happen every year such as the oil spills in Campos Basin (Brazil, 2011, 2012) (G1, 2011, Globalpost, 2012) and the Rena spill (New Zealand, 2011) (Nzherald, 2011). While humans restrict their attention only to average events (i.e. high-frequency/low-consequence), such large events (i.e. low-frequency/high-consequence) will continue to surprise and shape our world (Taleb, 2007).

Although most methodologies for quantitative ecological risk assessment (QERA) (e.g., (EPA, 1998, Pastorok et al., 2002, EEA, 1998, Bartell et al., 1992)) and case studies (e.g., (Naito et al., 2002, Pauwels, 2002, Bartell et al., 1999, Chen, 2005)) use models that are able to quantify ecological risks (hereafter ecorisks), they focus on ecorisks caused by regularly occurring events (e.g., chronic pollution, waste discharge, pesticide use on factory farm) of an industrial activity. They concentrate on events they already know, and fail to take into consideration what they do not know, causing them not to be open enough to imagine the “improbable”. In other words, they often ignore rare events (i.e. one which cannot be easily predicted because of the paucity of data about it; one for which the complexity of the system defies examination; one about which we have to wait too long to collect case-specific data (Uppuluri, 1980), e.g., marine oil spill, nuclear accident, eruption of a volcano) that have catastrophic consequences, albeit they are much less likely to occur. However, rare events do happen at some point, so that any attempt to accurately predict long-term ecorisks should take them into consideration.

As a result, it can be argued that the typical flaw consists of the missing link between ecorisks and industrial accidents. In order to tackle this limitation, the same authors of this work recently proposed a methodology for QERA of industrial accidents (Duarte and Droguett, 2011, Duarte, 2011). This work presents, in a preliminary form, an application of such methodology. By applying the methodology, we implemented a case-specific integrated model capable of quantifying ecorisks from accidental scenarios in the oil ship transportation to the Suape Port and Industrial Complex (SPIC), state of Pernambuco, northeastern Brazil.

The SPIC can be considered as one of the largest center of investments in Brazil. Today, the sum of investments is about US\$ 21,3 billion, spent by more than 100 active enterprises and other 35 in their implementation phase, such as the oil refinery, three petrochemical plants and four shipyards. Therefore, a great subject of research has been seen with the purpose of developing and improving the safe production and operation in SPIC (SUAPE, 2010). Indeed, oil will be supplied through an external harbor in SPIC. This harbor is expected to receive oil tankers of up to 170,000 DWT (Deadweight Tons) and is surrounded by very rich aquatic ecosystems such as beaches, estuaries, mangroves, coral reefs and coastal islands. Several native species are important to the Pernambuco state economy and to local human communities. Oil spills may cause catastrophic damage to the ecological health in SPIC and consequently economic and social impairments. Our assessment provides relevant and quantitative information that can support the decision-making process for preventing and managing such catastrophes. We also show that the methodology proves to be applicable, flexible, uses data efficiently and gives answers in a useful format.

In this paper, we start by briefly presenting the methodology (section 2). We then follow the steps of the methodology by means of an application. Section 3 provides some of the results obtained by the application of the methodology to the example under consideration, including the integrated stochastic model and the outputs of such model. The outputs are given in two ways: ecorisks related to each Accidental Scenario (hereafter AS) alone and categorized according to the International Union for Conservation of Nature (IUCN) quantitative risk criteria (IUCN, 2001).; and the cumulated ecorisks related to all ASs. A discussion of the outputs is also provided in section 3, its practical implications and potential future improvements. Finally, we

conclude by relating the most important goals and shortcomings of the model as well as future applications.

## 2. Methods and Materials

We use a QRA methodology (Duarte, 2011, Duarte and Droguett, 2011) directed to industrial accidents (low-frequency/high-consequence events) with potential to cause ecological adverse effects (i.e. changes that are considered undesirable because they alter valued structural or functional characteristics of ecosystems or their components (EPA, 1998)). The approach uses an interactive and flexible procedure that integrates information from four different specific studies that contribute to characterize ecorisks from industrial accidents, i.e.: (1) fate and transport modeling that describes and predicts dispersion and concentration of chemicals in the environment; (2) ecotoxicological assessment that translates a predicted chemical concentration into effects on individuals (e.g., increased mortality, reduced fecundity); (3) reliability analysis that predicts the occurrence of ASs; and (4) ecological modeling at population-level (i.e. population modeling) that translates mortality, growth, and reproductive effects on individuals into population-level effects (e.g., abundance decline, growth rate decline).

The last topic is particularly useful for the sake of more transparency and better risk communication, because the expected consequences of an accident to the ecosystem are expressed in more relevant units than individual-level effects (Forbes et al., 2010). They are expressed in terms of effects on populations of an indicative species strategically chosen to represent the ecosystem (e.g., species that are more sensitive, species of scientific and economic importance, rare and endangered species), taking into account the relationships between individuals, their life history, and population ecology. This way, the methodology can assess the risk of a population extinction (or decline) in the future, under the conditions that catastrophic accidents might happen.

The results of a QERA underpinned by this methodology are risk measures for each AS that take into account both the accident's frequency of occurrence and the magnitude of the consequence to a population of a native species. Such risk measures are expressed in terms of time and probability of extinction and can be categorized according to the IUCN risk criteria (IUCN, 2001).

Quantifying risks of each AS alone provides a basis for categorizing them, for comparing them against a no-accident scenario (no-AS), and for prioritizing management actions. However, it may also be useful to cumulate risks of all ASs as a basis for communicating the total ecorisk. For that, a FN curve was proposed (similar to the FN curve for the social risk in human QRA (CPR18E, 2005, CETESB, 2000)), where N is the average number of deaths in the population and F the cumulative frequency of accidents with potential to cause N or more deaths.

### 1.1. Problem characterization

To ensure that the results of this assessment would meet the needs of risk managers, the following specific objectives were taken into consideration: identify the significant ecorisks; examine the population dynamics (of a native species in the surrounding environment) when exposed to potential ASs for 100 years from now; quantify ecorisks of accidental events; be as conservative as possible in parameterization, so as to predict worst-case scenarios; provide numerical basis of knowledge for communicating risks; provide a basis for comparing, ranking and prioritizing ASs; conduct a sensitivity analysis that expresses changes in risks measures as a function of changes in the accidents' frequencies and its consequences; and deal with environmental stochasticity in time.

The SPIC is expected to receive oil tankers of up to 170,000 DWT. As this ERA was concerned only with accidents associated with transport and handling of crude oil, only transport units (i.e. oil tankers) and their routes to the external harbor were considered. This way, the coastal area was divided into 24 points (Figure 1) that represent possible locations for an accidental oil spill. Technical information associated with the activity were also considered, i.e. (SUAPE, 2010): transportation ships are double-walled oil tankers; about 1138 ships come in and out the harbor every year; 24 hours is the average duration of unloading per ship; 144 is the

average number of transshipments per year. Crude oil was the only chemical of concern.

Among the species in the wild fauna and flora of the coastal region of Suape, fishes were chosen to be analyzed because they are very useful as bioindicators of the ecosystem's health, i.e. (Karr and Chu, 1997): they have a relatively large size and the external effects of oil on larger wildlife species are often immediately apparent; life-history information is extensive for most fish species; their position at the top of the aquatic food web helps to provide an integrative view of the aquatic ecosystem; fishes are relatively easy to identify, what tends to decrease data collection errors; and fishes are typically present, even in the most polluted waters. A local fish population of a native species, i.e. *Diapterus rhombeus*, order Perciformes, family Gerreidae, common name Carapeba (in Portuguese) was chosen as indicative. This is one of the most common Gerreidae species in the estuarine region of Suape (SEAP/IBAMA/PROZEE, 2008). Local ecologists of the Tropical Fish Ecology Lab of the University of Pernambuco (LEPT) say that these fishes are thought to be more sensitive and therefore serve as an early warning indicator of ecological impacts. Also, they have significant economic and social importance, since local human communities feed on them as well as sell them as a means of livelihood.

Most of the required data for the QERA were available in the Environmental Impact Assessment (PETROBRAS/FADE, 2006) and in public databases (EPA, 2011, Froese and Pauly, 2011). Also, the LEPT provided demographic data about juvenile Carapebas, collected at the Suape shallow waters during 24 consecutive months (from March 2008 until February 2010). Juveniles use shallow waters and mangrove channels for breeding and for a growth phase, and migrate to areas of greater depth as soon as they become adults. The chosen assessment endpoint to provide information about the population of concern was its abundance. The initial population abundance was estimated at 22,111 based on the aforementioned population demographic data.

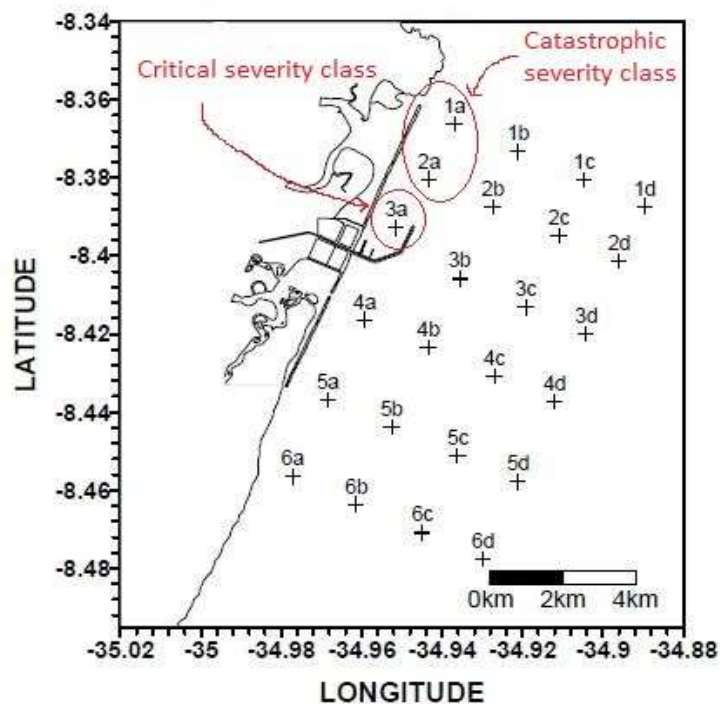


Figure 1. Possible points for an oil spill to be included in the QERA. Critical and Catastrophic severity sites are indicated.

## 1.2. Identification of hazards and consolidation of accidental scenarios

Each point in Figure 1 represents a possible location for an oil spill and so consolidates an AS. A Preliminary Hazard Analysis (PHA) (Ericson, 2005) was conducted in the 24 locations. Three of them (namely AS-1a, AS-2a and AS-3a) were classified with critical severity (i.e. class III, considerable ecological damage, reaching ecosystems beyond the boundaries of the

establishment and short recovery time) or catastrophic severity (i.e. class IV, considerable ecological damage, reaching ecosystems beyond the boundaries of the establishment and long recovery time). More specifically, AS-1a and AS-2a had catastrophic severity class IV and AS-3a had critical severity class III, as illustrated in the figure. These were selected for a more detailed analysis in the next step.

### 1.3. Exposure assessment

Oceanographic and meteorological conditions (i.e. coastal bathymetry, tides, the distribution of water temperature and salinity, currents, winds) influence the dispersion of oil in the ocean and thus the chemical concentration to which the fish population is exposed after an accident. An analysis of previous works conducted on the coast of Suape (Araujo et al., 2005, Araujo et al., 2010) has shown that conditions on the rainy season (from March to August) are similar and could be grouped in one meteorological scenario named “Winter”. Similarly, data on the dry season (from September to February) were grouped in the meteorological scenario named “Summer”. For each period of the year two tidal conditions were considered (i.e. Spring or Neap tide), based on information collected by tide gauges installed in coastal Suape. For a conservative assessment, all scenarios were simulated with the critical initial condition of flood tide, when the transport toward the shore is stronger. Hence, each of the three ASs from the previous step was divided into 4 new scenarios dependent on the season of the year (Summer or Winter) and the tidal range (Spring or Neap tide), resulting in the evaluation of  $3 \times 4 = 12$  ASs.

The Princeton Ocean Model (POM) (Ezer, 2005) was used as fate and transport model in order to describe the coastal ocean circulation in the region of concern. The POM is a three-dimensional, primitive equation, time-dependent,  $\sigma$  coordinate, free surface, estuarine and coastal ocean circulation model, incorporating a turbulence closure model to provide a realistic parameterization of the vertical mixing processes. The computational code of the POM, now in public domain, was developed in the 80's by Blumberg & Mellor (Blumberg and Mellor, 1987). Nowadays, it is one of the most tested and used frameworks by oceanographers to model coastal circulation (e.g., (Araujo et al., 2005, Araujo et al., 2010, Cummins and Oey, 1997, Kourafalou, 2001, Wheless and Valle-Levinson, 1996)). The original code of the POM does not simulate the dispersion of chemical plumes. For this reason, routines that calculate the advective-diffusive fate and transport of oil plume were added to the POM (Araujo et al., 2010). These routines also take into account the main physical-chemical mechanisms influencing on oil balance in tropical seawater: entrainment, emulsification and evaporation (Nazir et al., 2008). Once the ocean circulation was previously established by the POM, a new simulation was run by continuously injecting a certain flow rate of oil at the release point  $(x_r, y_r)$  on the sea surface.

In this study, the x-axis was considered perpendicular to the coastline in the northeast direction, the y-axis was parallel to the coastline in the northwest direction, and the z-axis was perpendicular upward with the origin at ocean surface. The simulation grid had its origin at the point of the coastline situated 2800 meters south of the external harbor (Figure 2).

The fish population under assessment covers three cells in the grid. For each AS,  $i$ , the concentration of oil as a function of time to which the fish population is exposed,  $C_i(x_0, y_0, z_0, t)$ , was defined as the arithmetic mean of the concentration predicted in each central point of those three cells, i.e.  $C_i(x_0, y_0, z_0, t) = [C_i(x_1, y_1, z_1, t) + C_i(x_2, y_2, z_2, t) + C_i(x_3, y_3, z_3, t)]/3$ . Subsequently, to select only ASs that may significantly contribute to the final ecorisks, we performed a conservative screening assessment of the toxicological effects at individual-level. We used the hazard quotient for that, i.e. the ratio of Predicted Environmental Concentration (PEC) to a Predicted No Effect Concentration (PNEC) (for more details on the hazard quotient approach see (EurEco, 1997)). More specifically, PEC was the local maximum of  $C_i(x_0, y_0, z_0, t)$  whereas PNEC was taken from ecotoxicological data in the reference (Eisler, 1975). The value for the PNEC was the LC0 (i.e. Lethal Concentration to 0% of test organisms) to crude oil of a related species that belongs to the same order of the Perciformes, i.e. *Parupeneus barberinus*. This extrapolation was needed because there were no such data on *Diapterus rhombeus*. We selected only those ASs which had hazard quotient greater than 0.01. All ASs in the Winter had

PEC/PNEC greater than 10.12. Conversely, all ASs in the Summer had PEC/PNEC equal to zero, because in this season the oil plume moves to the south and does not reach the population of concern.

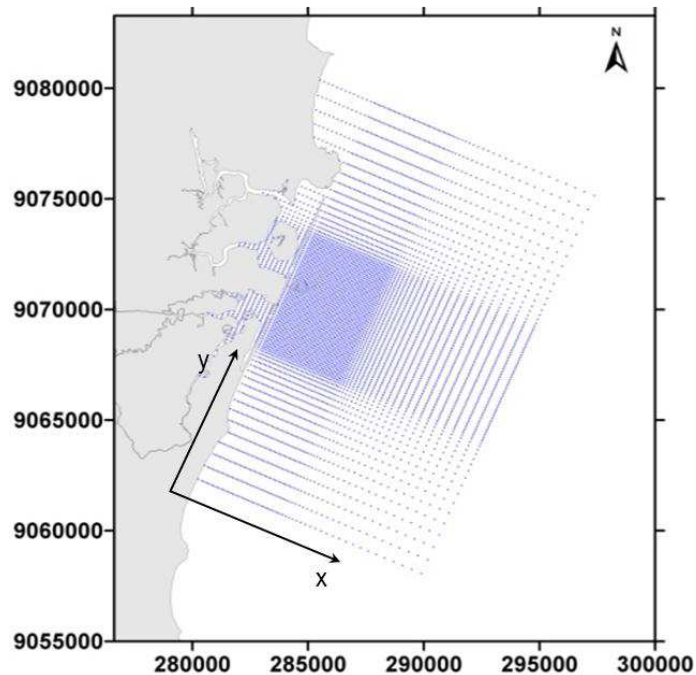


Figure 2. Discretization grid of the coastal region of the external harbor of SPIC (integration domain).

#### 1.4. Reliability analysis for frequency estimates

A screening reliability analysis was conducted based on generic frequencies of Loss of Containment Events (LOCs) for ships covering loading and unloading activities, and external impact. The reference (CPR18E, 2005) provides values for such frequencies per year. It is worth noting that such frequencies do not take into account specific circumstances that could reduce their values (e.g., safety management systems, alarms, automatic stops) as well as those that could increase their values (e.g., human error). Table 1 presents the considered LOCs for the selected ASs.

Fractional frequencies of the meteorological conditions were also defined as follows: 0.5 per year for both Summer (6 months) and Winter (6 months); and 0.5 per year for both Spring and Neap tides, because they alternate on a weekly basis. This way, each pair of meteorological condition (season and tide) had a frequency of 0.25 per year.

Table 1. Possible LOCs for AS-1a, AS-2a and AS-3a.

Accidental scenario	Full bore rupture of the unloading arm (L.1)	Leak of the unloading arm (L.2)	External impact, large spill (E.1)	External impact, small spill (E.2)
1a			X	X
2a			X	X
3a	X	X	X	X

#### 1.5. Population modeling

The modeled population was that described in section 3.1.2. Data was on one stage class only (i.e. juveniles), because they were collected in shallow coastal waters of Suape. Fishes migrate to deeper waters as soon as they become adults, so that the modeled population describes juvenile fishes only. The time-step of the model was 4 months, which is also approximately this species' generation time (i.e. 4.8 months) provided by life history data on *Diapterus rhombeus* in

the reference (Froese and Pauly, 2011).

A population model was then implemented in the population modeling and viability analysis software RAMAS GIS v. 5 (Akçakaya and Root, 2005). The model projected the population abundance (N) forward 100 years (or 300 time-steps) from the initial population abundance estimate (22,111 individuals) using the mathematical expression:  $N(t + 1) = R(t) \times N(t)$ , where  $R(t)$  is the growth rate of the population at time  $t$ . Temporal variability was incorporated into  $R(t)$  by establishing a lognormal distribution with a mean equal to 1.001 and a standard deviation (SD) equal to 0.01. We made a simulation with 10,000 replications. For each time-step, during each replication, a value to  $R(t)$  was randomly selected. Note that this is a baseline model that describes the juvenile population dynamics without chemical exposure. It represents a no-AS and will be used as benchmark against other models predictions.

### 3. Results

#### 3.1. Coastal circulation and oil plume dispersion

Figure 3 and Figure 4 are examples of the space-time evolution of oil in the ocean after an oil spill at location 3a (some of fate and transport simulation results) considering meteorological conditions Winter/Spring tide.

#### 3.2. Exposure-response assessment

Data from a related fish species (i.e. *Parupeneus barberinus*) provided three points of lethal concentration (i.e. LC0, LC50 and LC100) to crude oil (EPA, 2011). A logarithmic trendline was added to these points, since it was expected that the rate of change in the function quickly increases and then levels out. Also, it was the best-fit curved line among several attempts of other different trend or regression types. The R2 value was 0.9953, which indicates a good fit of the dose-response data. The fitted curve was then defined as a dose-response function (i.e. fraction of mortality as a function of concentration of oil in water in ml/L) for the species of concern, i.e.  $M_i(t) = 0.2926 \cdot \ln(C_i(x_0, y_0, z_0, t)) - 0.0173$ , where  $M_i$  is the fraction of mortality caused by the occurrence of AS i.

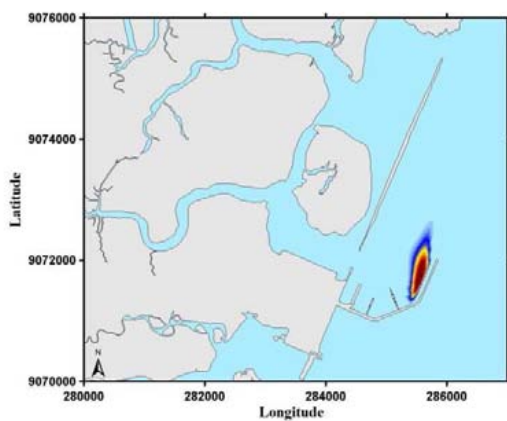


Figure 3. Dispersion of the oil plume 3 hours after AS-3a-winter-spring tide.

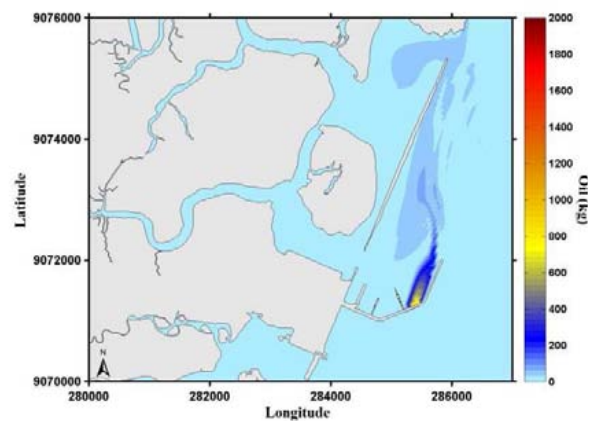


Figure 4. Dispersion of the oil plume 19 hours after AS-3a-winter-spring tide.

#### 3.3. Frequency estimates

Table 2 presents the resulting frequency estimates along with the predicted concentration from the previous step (exposure assessment).

Table 2. The concentration as a function of time to which the fish population is exposed,  $C_i(x_0, y_0, z_0, t - T)$ , where  $t$  is the discrete simulation time-step (4 months),  $T$  is the time-step at which the accidental scenario  $i$  occurs, and  $F_i(y^{-1})$  the frequency of occurrence of  $i$ .

Accidental scenario	$C_i(x_0, y_0, z_0, t - T)$	$F_i(y^{-1})$
3a-winter-neap tide	$\begin{cases} 17.49, & \text{for } t = T \\ 0, & \text{for } t > T \end{cases}$	$0.09504198 \times 0.25 = 0.02376049$
3a-winter-spring tide	$\begin{cases} 10.12, & \text{for } t = T \\ 0, & \text{for } t > T \end{cases}$	$0.09504198 \times 0.25 = 0.02376049$
2a-winter-neap tide	$\begin{cases} 21.47, & \text{for } t = T \\ 0, & \text{for } t > T \end{cases}$	$1.98 \times 10^{-6} \times 0.25 = 4.9 \times 10^{-7}$
2a-winter- spring tide	$\begin{cases} 14.91, & \text{for } t = T \\ 0, & \text{for } t > T \end{cases}$	$1.98 \times 10^{-6} \times 0.25 = 4.9 \times 10^{-7}$
1a-winter-neap tide	$\begin{cases} 23.79, & \text{for } t = T \\ 0, & \text{for } t > T \end{cases}$	$1.98 \times 10^{-6} \times 0.25 = 4.9 \times 10^{-7}$
1a-winter- spring tide	$\begin{cases} 18.10, & \text{for } t = T \\ 0, & \text{for } t > T \end{cases}$	$1.98 \times 10^{-6} \times 0.25 = 4.9 \times 10^{-7}$

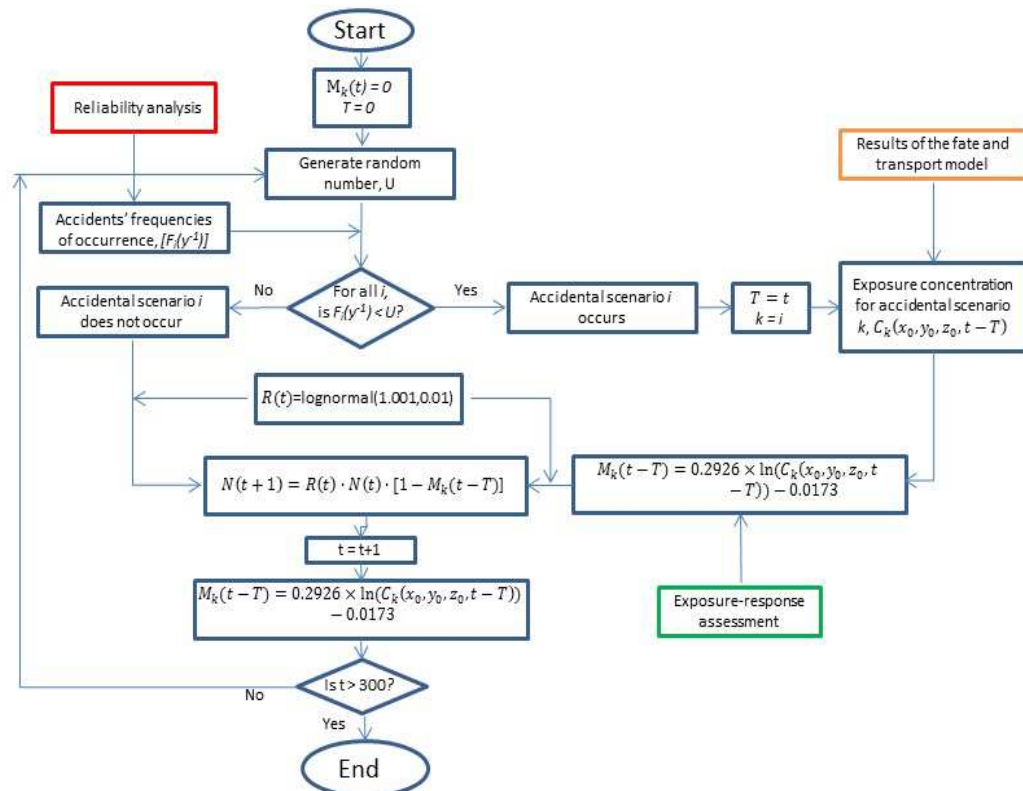


Figure 5. Conceptual diagram that represents one replication out of 10,000 for simulating impact of potential accidental scenarios. Different colors are used to differentiate information from different specific studies that underpin the QERA.

### 3.4. The integrated stochastic models

Three new models were implemented to represent AS-1a, AS-2a and AS-3a. To do so, we incorporated to the no-AS model (section 1.5) a source of environmental stochasticity (known as catastrophe) that is independent of the year-to-year temporal variation of the growth rate  $R(t)$ .



We included two catastrophes for each of the three new models, representing their possible meteorological conditions in the Winter (i.e. Neap tide or Spring tide). ASs in the Summer were not modeled because in this season the oil plume moves to the south and does not reach the population of concern.

All catastrophes had a given frequency of occurrence and predicted exposure (Table 2). Thus, for each time-step of each replication (total of 10,000 replications), each of the two catastrophes was randomly selected to strike (or not) according to its frequency of occurrence. If it does, it causes a certain fraction of mortality (originated from the dose-response function) to the population from that time-step on. This is modeled by the following mathematical expression:  $N(t + 1) = R(t) \cdot N(t) \cdot [1 - M_k(t - T)]$ , where  $k$  is the randomly selected AS to strike,  $M_k(t - T) = 0.2926 \times \ln(C_k(x_0, y_0, z_0, t - T)) - 0.0173$ , and  $T$  the time-step at which  $k$  strikes. Table 2 shows the parameter values for each AS. Figure 5 illustrates this simulation process for one replication.

### 3.5. Risk quantification and evaluation

The stochastic models predictions were used to construct probability-consequence curves such as the terminal extinction risk curve shown in Figure 6. The resulting curve for each AS model could be compared to the curve of the no-AS model. Extinction risk curves for no-AS, AS-1a and AS-2a are statistically superimposed, so the potential occurrence of these ASs cause the fish population of concern to face background risks only (i.e. the chance that any population has to naturally become extinct (Akçakaya et al., 1997)). Conversely, the potential occurrence of AS-3a causes a significant added risk of extinction. According to the IUCN risk criteria (IUCN, 2001), the potential occurrence of AS-3a causes the fish population to be categorized as “Vulnerable” (Figure 7).

#### 3.5.1. Cumulating ecorisks from all accidental scenarios

Here, all critical accidental scenarios are considered, which were selected up to the current step of methodology (risk quantification and evaluation), i.e. AS-1a, AS-2a and AS-3a in the Winter. Table 3 shows a list of these ASs (and the number of deaths caused by each of them) sorted by their frequencies of occurrence. By cumulating the frequencies for which the number of deaths of a particular accidental scenario,  $N_i$ , is greater than or equal to  $N$ , the FN curve was built (Figure 8). The y-axis is in logarithmic scale and that is because the frequency of occurrence of 20121 or more deaths was defined at  $10^{-8}$ /year instead of zero. The value of  $10^{-8}$ /year is the frequency criterion (in the fourth step of the methodology, i.e. frequency estimates) to screen out accidental scenarios that are irrelevant in terms of risk. Therefore, ecorisks from any event that occurs with a frequency less than that are considered to be none (zero).

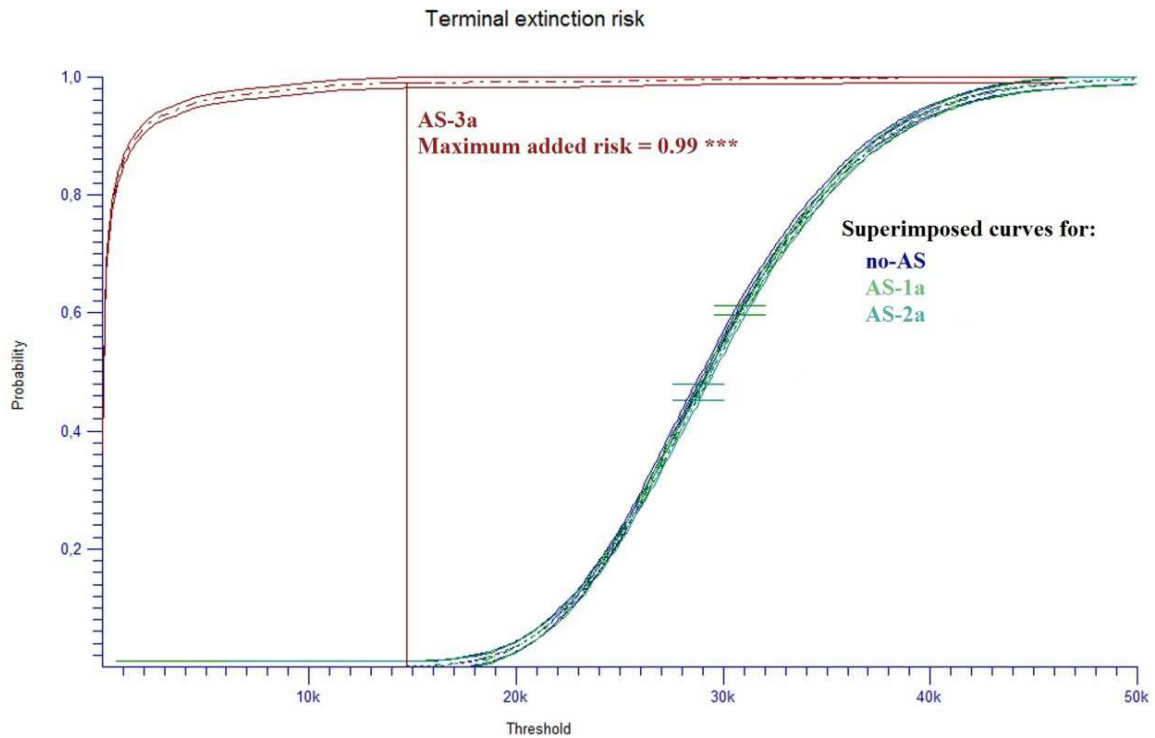


Figure 6. Comparison of a no-AS with each of the ASs, in terms of terminal extinction risk. Each point on a curve can be interpreted as “there is a Y% risk that, 100 years from now, the population abundance will be less than X”. The dotted line indicates the average value, whereas the solid lines the 95% confidence intervals. The 3 vertical bars with two horizontal tabs represent the maximum vertical difference between the no-AS scenario and an AS. The value of the difference for AS-3a is reported, and the Kolmogorov-Smirnov test statistic D (which is the maximum vertical difference), with the asterisks giving the significance level (\*\*\*: 0.001), based on two-sample Kolmogorov-Smirnov test (Akçakaya and Root, 2005).

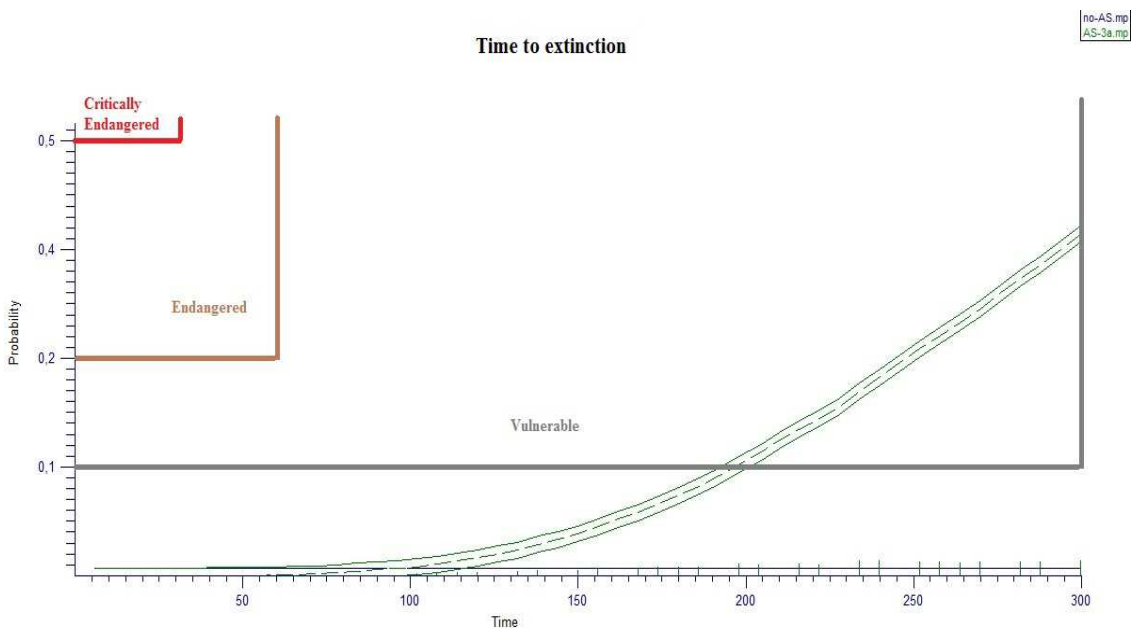


Figure 7. Risk categorization according to IUCN.

Table 3 – List of accidental scenarios and their respective number of deaths (N) sorted by their frequencies (per year). The frequency of N or more deaths is calculated by cumulating the sorted list of frequencies.

Accidental Scenario	Number of deaths (N)	Frequency (per year)	Frequency of N or more deaths (per year)
1a-winter-neap tide	20121	0.00000049	1E-8
2a-winter-neap tide	19458	0.00000049	0.00000049
1a-winter-spring tide	18352	0.00000049	0.00000098
3a-winter-neap tide	18131	0.02376049	0.00000147
2a-winter-spring tide	17025	0.00000049	0.02376196
3a-winter-spring tide	14593	0.02376049	0.02376245
	0	-----	0.04752294

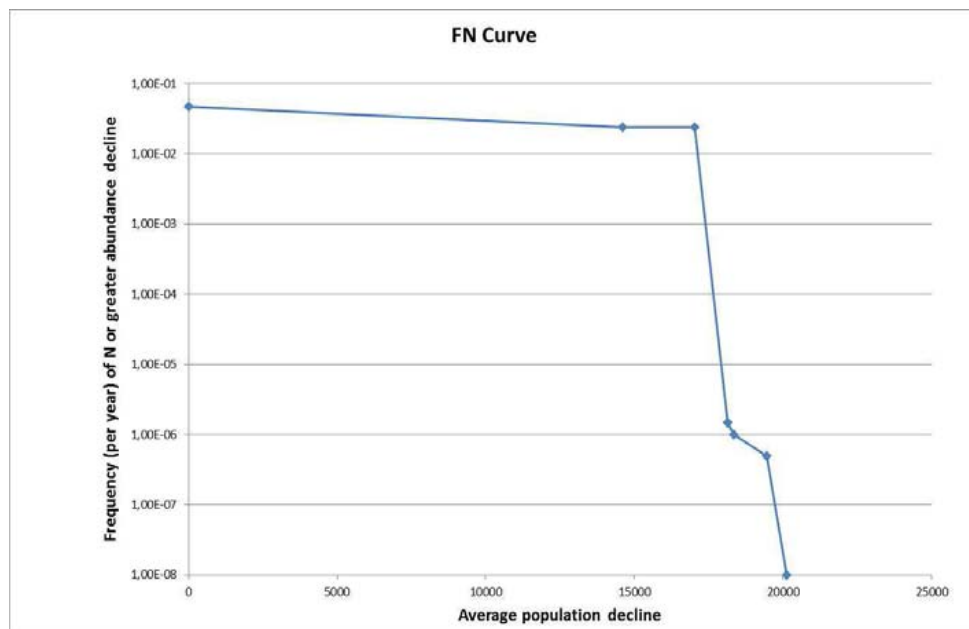


Figure 8. FN curve for cumulating ecorisks of all accidental scenarios.

#### 4. Conclusions

This paper presented a QERA underpinned by a methodology capable of quantifying ecorisks caused by events with low frequency of occurrence but that may cause catastrophic ecological damage. The main goal of the proposed methodology was to integrate information from four different studies that can contribute to quantify ecorisks originating from rare events, namely (1) fate and transport modeling, (2) ecotoxicological assessment, (3) reliability analysis, and (4) ecological modeling at population-level.

The results showed that ecorisks from AS-3a cause the bioindicator population to be categorized as “Vulnerable” (Figure 7). Conversely, other accidental scenarios cause background risks only (Figure 6). From this point of view, management actions should be taken to reduce the frequency of occurrence and/or the magnitude of the consequences of AS-3a until risks reach an acceptable level (e.g., “Not Threatened” IUCN risk category).

There are some limitations in this QERA, i.e.: (1) frequencies were estimated based on average situations and did not take into account specific circumstances of the AS under assessment (e.g., control measures); (2) fate and transport model was deterministic for each group

of meteorological condition (total of four groups); (3) ecotoxicological data to build a dose-response curve was extrapolated from a related species; and (4) ecorisks related to ASs in the Summer were not considered because the oil plume does not reach the population chosen as bioindicator, although it may reach others populations to the south.

As the methodology is interactive, any new information and revaluation can be incorporated into the QERA at any time, starting a new round in order to improve results. For instance, a sensitivity analysis (Duarte, 2011) showed that changes in both frequency and consequence of AS-3a cause significant changes in risk estimates. Hence, some further work to effectively tackle the aforementioned limitations would be to: (1) conduct a more detailed reliability analysis for estimating more accurate frequencies; (2) incorporate meteorological stochasticity into the fate and transport model for a more accurate exposure assessment; (3) perform ecotoxicological tests with *Diapterus rhombeus* and crude oil; and (4) include another fish population to the south of the release points and build a metapopulation model with potential for migration between the two populations so that ecorisks related to ASs in the Summer could be also quantified.

## References

- AKÇAKAYA, H. R., BURGMAN, M. A. & GINZBURG, L. R. 1997. *Applied Population Ecology: principles and computer exercises using RAMAS EcoLab 2.0*, Setauket, New York, Applied Biomathematics.
- AKÇAKAYA, H. R. & ROOT, W. 2005. *RAMAS GIS: Linking Spatial Data with Population Viability Analysis (version 5)*, Setauket, New York, Applied Biomathematics.
- ARAUJO, M., LERITHIER, D., SILVA, M. A., LUNA, M. C. & MEDEIROS, C. 2005. Tidal turbulence and eddy-viscosity in coastal waters at Northeastern Brazil. *J Coastal Res*, 21, 18-27.
- ARAUJO, M., SILVA, M. A., SILVA, R. A. & VELEDA, D. R. A. 2010. Estudo da dispersão de vazamentos acidentais de hidrocarbonetos na região costeira de Suape-PE. *Refinaria Abreu e Lima - RNEST*.
- BARTELL, S. M., GARDNER, R. H. & O'NEILL, R. V. 1992. *Ecological Risk Estimation*, Chelsea, MI, Lewis Publishers.
- BARTELL, S. M., LEFEBVRE, G., KAMINSKI, G., CARREAU, M. & CAMPBELL, K. R. 1999. An ecosystem model for assessing ecological risks in Québec rivers, lakes, and reservoirs. *Ecol Modell*, 124, 43-67.
- BLUMBERG, A. F. & MELLOR, G. L. 1987. A description of a three-dimensional coastal ocean model. In: HEAPS, N. S. (ed.) *Three-dimensional coastal ocean models*. AGU.
- CETESB 2000. *Manual de orientação para elaboração de estudos de análise de riscos*, São Paulo, Companhia Ambiental do Estado de São Paulo (CETESB).
- CHEN, C. S. 2005. Ecological risk assessment for aquatic species exposed to contaminants in Keelung River, Taiwan. *Chemosphere*, 61, 1142-1158.
- CPR18E 2005. *Guidelines for quantitative risk assessment (the "Purple book")*.
- CUMMINS, P. F. & OEY, L. Y. 1997. Simulation of barotropic and baroclinic tides off Northern British Columbia. *J. Phys. Ocean.*, 27, 762-781.
- DUARTE, H. O. 2011. *A methodology for quantitative ecological risk assessment for industrial accidents*. Master's dissertation, Universidade Federal de Pernambuco (UFPE).
- DUARTE, H. O. & DROGUETT, E. L. 2011. Uma abordagem para a quantificação de riscos ecológicos inerentes a acidentes industriais com substâncias tóxicas. *XLIII Simpósio Brasileiro de Pesquisa Operacional (SBPO)*, Ubatuba-SP.
- EEA 1998. *Environmental Risk Assessment - Approaches, Experiences and Information Sources*, London, UK, EEA (European Environment Agency).
- EEA 2003. *Mapping the impacts of recent natural disasters and technological accidents in Europe*, Copenhagen, Environmental Issue Report.
- EISLER, R. 1975. Acute Toxicities of Crude Oils and Oil-Dispersant Mixtures to Read Sea Fishes and

- Invertebrates. *Isr J Zool*, 24, 16-27.
- EPA 1998. *Guidelines for Ecological Risk Assessment*, Washington, DC.
- EPA. 2011. *U.S. EPA ECOTOX, Version 4, Web site. The ECOTOX (ECOTOXicology) database* [Online]. Available: [http://cfpub.epa.gov/ecotox/ecotox\\_home.cfm](http://cfpub.epa.gov/ecotox/ecotox_home.cfm) [Accessed sep-08-2011].
- ERICSON, A. C. 2005. *Hazard Analysis Techniques for System Safety*, Hoboken, New Jersey, Wiley.
- EURECO 1997. *Review of selected schemes developed for environmental risk assessment of substances hazardous for the aquatic environment*, Luxembourg, Institut for Inland Water Management and Waster Water treatment (RIZA).
- EZER, T. 2005. Entrainment, diapycnal mixing and transport in three-dimensional bottom gravity current simulations using the Mellor-Yamada turbulence scheme. *Ocean Modelling*, 9, 151-168.
- FORBES, V. E., CALOW, P., GRIMM, V., HAYASHI, T., JAGER, T., PALMQVIST, A., PASTOROK, R., SALVITO, D., SIBLY, R., SPROMBERG, J., STARK, J. & STILLMAN, R. A. 2010. Integrating population modeling into ecological risk assessment. *Integrated Environmental Assessment and Management*, 6, 191-193.
- FROESE, R. & PAULY, D. 2011. *Fishbase, version (08/2011). World Wide Web eletronic publication*.
- G1. 2011. *Após vazamento de óleo, Chevron tenta selar poço na Bacia de Campos* [Online]. Available: <http://g1.globo.com/> [Accessed nov-11-2011].
- GLOBALPOST. 2012. *Second Chevron oil spill in Brazil halts production* [Online]. Available: <http://www.globalpost.com/dispatches/globalpost-blogs/que-pasa/second-chevron-oil-spill-brazil-halts-production> [Accessed Apr-2012].
- IUCN 2001. *IUCN Red List Categories: Version 3.1*, Gland, Switzerland and Cambridge, UK, IUCN Species Survival Comission.
- KARR, J. R. & CHU, E. W. 1997. Biological monitoring: essential foundation for ecological risk assessment. *Hum Ecol Risk Assess*, 3, 993-1004.
- KOURAFALOU, V. H. 2001. River plume development in semi-enclosed Mediterranean regions: North Adriatic Sea and Northwestern Aegean Sea. *J. Mar. Sys.*, 30, 181-205.
- NAITO, W., MIYAMOTO, K.-I., NAKANISHI, J., MASUNAGA, S. & BARTELL, S. M. 2002. Application of an ecosystem model for aquatic ecological risk assessment of chemicals for a Japanese lake. *Water Res*, 36, 1-14.
- NAZIR, M., KAHN, F., AMYOTTE, P. & SADIQ, R. 2008. Multimedia fate of oil spills in a marine environment - An integrated modelling approach. *Process Saf Environ Prot*, 86, 141-148.
- NZHERALD. 2011. *Rena oil spill* [Online]. Available: [http://www.nzherald.co.nz/rena-oil-spill/news/headlines.cfm?c\\_id=1503203](http://www.nzherald.co.nz/rena-oil-spill/news/headlines.cfm?c_id=1503203) [Accessed Dec-2011].
- PASTOROK, R. A., BARTELL, S. M., FERSON, S. & GINZBURG, L. R. 2002. *Ecological modeling in risk assessment: chemical effects on populations, ecosystems and landscapes*, CRC Press LLC.
- PAUWELS, S. J. 2002. *Fish Population Modeling: Data Needs and Case Study*, CRC Press LLC.
- PETROBRAS/FADE 2006. *Estudo de Impactos Ambientais da Refinaria do Nordeste. EIA-RIMA RNEST*, Recife, PE, Centro de Documentação da CPRH.
- SEAP/IBAMA/PROZEE 2008. *Boletim Estatístico de Pesca Marítima e Estuarina do Nordeste do Brasil - 2006*, Tamandaré, PE, Centro de Pesquisa e Gestão de Recursos Pesqueiros do Litoral Nordeste - CEPENE.
- SUAPE. 2010. *Suape - Complexo Industrial Portuário Governador Eraldo Gueiros* [Online]. Available: <http://www.suape.pe.gov.br/> [Accessed dec-27-2011].
- TALEB, N. N. 2007. *The black swan: the impact of the highly improbable*, New York, USA, Random House.
- UPPULURI, V. R. R. 1980. *Rare events: a state of the art*, TN (USA), Oak Ridge National Lab.
- WHELESS, G. H. & VALLE-LEVINSON, A. 1996. A modeling study of tidally driven estuarine exchange through a narrow inlet onto a sloping shelf. *J Geoph Res*, 101, 675-687.