Support methodologies for oil spill prevention and response in a coastal lagoon (Portugal) integration of physical, environmental and socioeconomic dimensions

Eduardo R. Oliveira [(a)], Bruno Silveira [(a)], Fátima L. Alves [(a)]

(a) Department of Environment and Planning & CESAM
University of Aveiro, Portugal
eduardo.oliveira@ua.pt / brunosilveira@ua.pt / malves@ua.pt

ABSTRACT

Oil spill accidents can be caused by several risk factors associated to maritime transport and port activities, which cannot always be predictable or controllable. Therefore, it is essential to support prevention and contingency plans, which effectiveness is crucial to produce adequate responses and minimize resulting impacts.

The Ria de Aveiro (Portugal) is a wide coastal lagoon ecologically diversified, conjoined with a densely populated pole with several economic activities concentrated. One of the main objectives of this work is to construct a geographic information system database with crucial data, to contribute as an important support tool for the optimization of civil protection assets in the occurrence of an oil spill event.

The presented methodologies are based on: i) the Environmental Sensitivity Index developed by the North American National Oceanic And Atmospheric Administration (USA), with special focus on ecologic and geomorphologic domains – habitats and shoreline, respectively; and ii) the Global Vulnerability Index applied for the Bay of Biscay (Spain), that, adds a socioeconomical factor related to oil spills. However, during the development of present work, none of these methodologies, was considered to be able to entirely assess the study area, which leads to the necessity to adapt to an own approach. The introduced changes include extra categories in shoreline classification, considerations for the lagoon specifications, an adapted physical vulnerability index for lagoons, differentiated aspects for highly protection status areas, qualitative assessment of socioeconomic features and an access and operability index for contingency means deployment.

KEY WORDS: *Hydrocarbons, Risk Assessment, Geodatabase, Ria de Aveiro*

INTRODUCTION

Maritime transport and port activities are amongst the major risk factors affecting coastal areas. According to the International Tanker Owners Pollution Federation (ITOPF, 2012), the list of large acute oil spill accidents is mostly associated with port operations, collisions, fires and explosions.

Due to their configuration, coastal lagoons are particularly exposed to the pollutants negative impacts, not only because of their ideal location to accommodate large maritime ports, but also because they often concentrate important biologic and socioeconomic resources, posing special problems for cleanup operations (O'Sullivan & Jacques, 1998).

Oil spill accidents may vary according to a range of factors, from: spill size, location, type of oil, or weather conditions (ITOPF, 2002; White, 2002; Santos & Andrade, 2009). Since they cannot always be predictable or controllable, prevention is usually the only available first line of defence (EPA, 1999).

In order to produce effective counteracting actions during oil spill events, it is essential to previously identify the most critical areas, otherwise resulting impacts can get worse if adequate contention and cleaning measures are not promptly taken (Pincianato *et al*., 2009; Vafai, *et al*. 2013).

The present case study introduces the Ria de Aveiro, a wide coastal lagoon located on the Central Region of Portugal. Covering almost 12 thousand hectares includes a large multifunctional port and it is considered as an important biodiversity zone. Located on a highly populated area, concentrates several types of anthropic activities, including fisheries, tourism, harbour, leisure and recreation.

BACKGROUND

In 1979, United States National Oceanic and Atmospheric Administration (NOAA) introduced the Environmental Sensitivity Index (ESI) maps. Ever since, they are still one of the most broadly used support mechanisms, contributing to reduce environmental consequences of spills and cleanup efforts (NOAA, 2002). The concept of Sensitivity, firstly associated to the concept of Susceptibility in landslides risk assessment, defines *the "…likelihood of an area being affected by an event, on the basis of local (…) conditions not accounting the probability of occurrence of the dangerous phenomena."* (Guzzetti, 2006; Zêzere, 2011). Applicable to coast, estuaries and river environments, ESI maps are composed by a concise summary of key features such as a shoreline geomorphology sensitivity rank to oiling, and biological and human-use at-risk resources. ESI maps also provide complementary guidelines for decision-making support systems in oil spill contingency plans (NOAA, 2002; Vafai *et al*., 2012).

NOAA proposed another methodology to be applied in small rivers and streams. The Reach Sensitivity Index (RSI) consists on the integration of the original ESI methodology, with other elements: navigation, water flow patterns, stream size, suitable collection points, channel leakage, bifurcation and oil persistence time (Hayes *et al.*, 1997).

Another concept under the scope of risk assessment is vulnerability. The definition of vulnerability is often referred as the extent of which a system is susceptible to sustain damage from (IPCC, 2001), or the degree of loss of a community or an area towards defined hazards (ESPON, 2003; Kumpaleinen, 2006; Santos *et al*, 2012).

Castañedo *et al*., 2009, developed an oil spill vulnerability assessment integrating physical, biological and socioeconomic dimensions, for the Cantabrian coast in Spain. Unlike NOAA's ESI maps, this method includes a quantitative approach, based on three specific indexes, applied to shoreline segments and compared with each other.

Ng *et al*., 2008, describe an oil spill support methodology, applied to the Pulau Pinang eastern coast (Malaysia). Despite using the term Vulnerability, authors use a modified version of ESI maps, adjusted with environmental and socioeconomic features. They represent a qualitative assessment of existing biodiversity conservation protection status, and human activities or uses.

Regarding the application of similar studies in Portugal, one of the first methodologies is included on the Portugal Mainland Coastal Atlas (MARETEC, 2007). Based on NOAA's ESI maps, this study adds a socioeconomic index, established according to five qualitative classes. More recently, Leal, 2011, assessed the sensitivity of hydrocarbons maritime pollution planning and response, applied to a southwest Algarve coastal area. Particularly adapted to high use recreational areas, this study includes accessibilities and beach carrying capacity factors.

METHODS

This study is the result of an extended bibliographic research over numerous case studies and oil spill accident support methodologies (Figure 1). Methods were tested and applied on a geodatabase containing physical, biological and socioeconomic elements of the Ria de Aveiro.

This study comprehends three independent indexes and respective cartography. Their application is focused on the Port of Aveiro jurisdiction area.

The first index is a modified version of NOAA's ESI maps. Considering the morphological specificities of the study area, it was necessary to include extra shoreline categories.

In this context, code *8F - Vegetated, steeply-sloping bluff* is used, even for non-riverine locations. This type of shoreline occurs in certain segments of the Vouga Estuary, which is located near the eastern area of the Ria de Aveiro (Vaz *et al.*, 2005).

Also, where smaller streams are present, code *10F - Anastomising channels* is used, which according to the RSI guidelines corresponds to a case of maximum oil spill sensitivity (Hayes *et al.*, 1997). As for the rest of biological and socioeconomic resources, the original ESI maps methodological guidelines were followed, except for the incorporation of other occurring recreational activities: kitesurfing, paddling, rowing, stand-up-paddle surfing, boat tours, windsurfing and sailing.

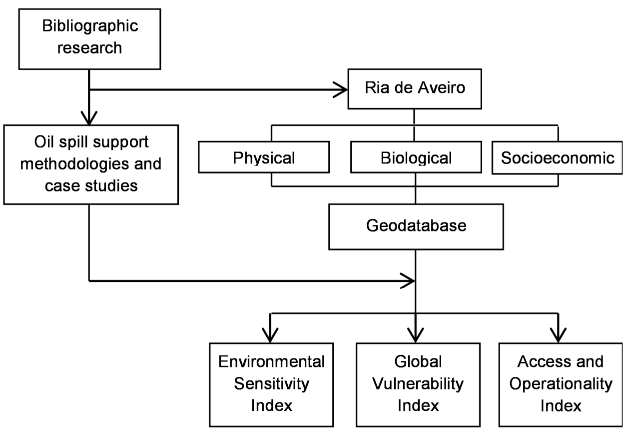


Figure 1. Methodological scheme

The second presented methodology is related to a global vulnerability index. This index, I_G, is given by Eq. (1), corresponding to the weighted average of physical, biological, and socioeconomic indexes - I_P, I_B and I_E. Both physical and biologic indexes, are based on Castañedo *et al*., 2009 study, and the socioeconomic index, is based on Ng *et al*., 2009 and MARETEC, 2007 methodologies.

$$I_G = (I_P + I_B + 2I_E) \quad (1)$$

According to Castañedo *et al*., 2009 the physical index, assesses the potential impact of an oil spill, based on the self-cleaning capacity of coastal segments, depending on wave exposure and mean shoreline slope. However, for areas such as estuaries, the method assumes the maximum physical vulnerability index value due to their slow self-cleaning capacities. For this case study, its direct application would not allow to distinguish areas with different physical characteristics, contributing for the overall generalization of the global vulnerability index results. Considering that wave exposure is almost inexistent in estuarine and lagoons environments, the present study suggests an alternative physical index definition, based on the average shoreline slope, *SP*, and dominant wind exposure, *E*, estimated by Eq. (2):

$$IP = E + SP = O + S + SP \quad (2)$$

Exposure, *E*, is calculated by the sum of the orientation, *O*, and the sinuosity, *S*, of the assessment unit.

According to data from local meteorological stations (MAOT & INAG, 2011), dominant winds, both in terms of frequency and intensity, have NW and SE directions, and NE and SW are at a medium level. Each shoreline segment azimuth orientation corresponds to the values of the following scale: 1: *azimuths between 108º-180º or 288º-0º*; 2: *azimuths between 18º-72º or 198º-252º*; and 3 for the rest.

The sinuosity parameter, *S*, acts as a correction of the orientation factor and is determined according to Castañedo *et al*., 2009 methodology. Exposed shores are associated with low sinuosity, while high sinuosity is associated with increased oil persistence time.

In terms of shoreline slope, each segment is classified according to the following scale: 1: *SP > 1/2 (steep)*; 2: *1/10<SP<1/2 (intermediate)*; 3: *SP<1/10 (smooth)*. This simplified version of the original method enables the use in areas with limited availability of data.

According to Castañedo *et al.,* 2009, the biological index, I_B, is given by Eq. (3):

$$I_B = I_C + I_S + I_r \quad (3)$$

I_C, corresponds to the conservation state, including the current structural and functional status of each water body segment; I_S, the singularity value, considers the existing legal conservation protection status; and I_r, the resilience factor, is associated to the ability of local habitats to recover from perturbations caused by oil spill.

While I_C is determined in terms of the physical, chemical and biological conditions of the water body (Pio & Henriques, 2000), I_S is estimated by the percentage of vegetation cover. As for the I_S value, some modifications are introduced. The Ria de Aveiro water body and adjacent areas are classified has Special Protection Zone (Natura

2000 Network), which would result on the single use of the maximum singularity score. Again, this would reflect on the overall generalization of results, so an adapted classification is described on Table 1.

The socioeconomic index defined by Castañedo *et al*., 2009 consists on the assessment of the economic damage assigned to each shoreline segment and cleaning costs. Both reference cleanup costs and required data for fishery, shellfish, tourism, harbour activity and recreation, are based on the Spanish national data availability and historical records. However, due to the limited availability of local data, other methodologies were followed on the Ria de Aveiro case study.

Table 1. Singularity value, I_S, classification.

I_S score	*Area conservation status*
0	No legal conservation status
1	Natura 2000 Network
2	National Ecological Reserve
3	Agricultural Pollution Vulnerable Area Ecological Protection Project
4	Natural Reserve

Although the MARETEC, 2007 socioeconomic index was developed according to the Portuguese coastal scenario, it lacks references to particular human activities or associated infrastructures. On the other hand, the Ng *et al*., 2008 socioeconomic index is less subjective, but is organized according to the Malaysian importance standards, which are different to this case study. Hence, an alternative method is described in Table 2, establishing an adaptation of these two socioeconomic indexes.

The third methodology corresponds to the access and operability index, providing relevant information for local authorities and optimization of contingency means. The access index is based on Leal, 2011 method, including the location of fire stations, civil protection headquarters, and respective best available accesses to each shoreline segment. The quality of each connection is assessed in terms of width and pavement type: 1: *concrete roads and concrete walking/cycling paths wider than 2.5 m*; 2: *unpaved roads wider than 2.5 m*; 3: *unpaved roads and paths narrower than 2.5 m*.

Table 2. Socioeconomic index, I_E, classification.

I_E score	*Description*
5	Recreational beach and urban areas presenting high concentrations of patrimonial, cultural and infrastructural aspects (roads, walk and bicycle paths, marinas, docks, commercial areas, hotels, restaurants, bars and sport facilities).
4	Remaining urban areas, without recreation beach facilities, or with reduced recreational use, although concentrating commercial, industrial, institutional and residential areas, and infrastructures which oil spill may affect their immediate activities or usage.
3	Agriculture, aquaculture, salt pans, marinas, docks, camping sites, recreational and nautical sport areas (kitesurf, windsurf, sailing, stand-up-paddle, paddling and rowing).
2	Forest areas.
1	Remaining areas, including military, wetlands, bare or unknown usage areas.

The operability index is applied to each shoreline segment, estimated in qualitative terms, considering access proximity and terrain availability for contingency means deployment. Proximity is scored accordingly to: 1: *near to concrete roads and concrete walking/cycling paths wider than 2.5 m*; 2: *near to unpaved roads wider than 2.5 m*; 3: *near to unpaved roads and paths narrower than 2.5 m, i.e., walk-only access*; 4: *no land access*. The terrain availability factor is defined in terms of the existence of free adjacent terrain (1: < *800* m^2; 0: > *800* m^2). The final operability index score is comprehended between 1 and 5, where higher values correspond to areas with increased accessibility constraints.

RESULTS

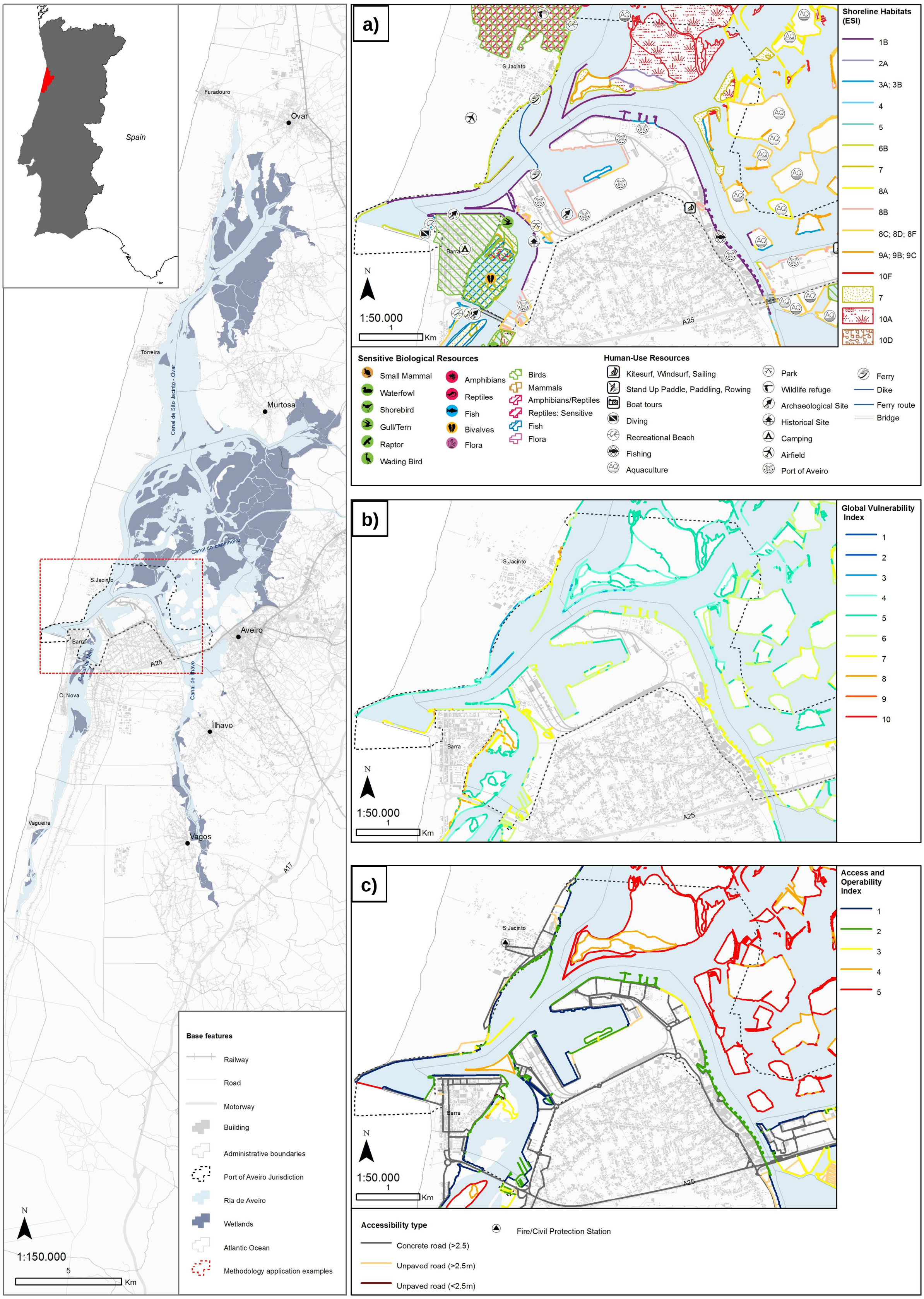
The application of the three indexes is shown on Figure 2, including preliminary detail maps of the Port of Aveiro jurisdiction area. Although they represent independent concepts and approaches, this simultaneous representation enables the possibility of a compared spatial analysis.

According to the ESI map of Figure 2 a), there are several types of shoreline classes, covering the whole range of the sensitivity index score. The lowest sensitivity shoreline type is classified as *1B – Exposed, solid man-made structures*, concentrating around the port and lagoon mouth areas. The highest sensitive locations correspond to wetlands, classified as *10A – Salt-and brackish-water marshes*. Figure 2 a) also indicates the presence of sensitive biological resources, in particular around the Natural Reserve of Dunes of S. Jacinto and the bridge of Barra. As for human-use resources, there are several high-use and recreation areas, resource extraction sites, and water associated historical and archaeological sites.

The several layers of information contained in ESI maps, allow the immediate identification of the most sensitive elements and areas. Although, higher scales tend to increase the concentration of featured elements and are prone to cause interpretation difficulties.

The image on Figure 2 c), shows shoreline segments classified between 3 and 8. The Global Vulnerability Index map integrates an objective assessment in terms of physical, biological and socioeconomic dimensions presenting the level of vulnerability of each shoreline segment without detailing the exposed elements. The most vulnerable zone is at the east side of Barra.

The image of Figure 2 d), displays the results for Access and Operability Index, including the location of a volunteer fire-station in S. Jacinto. The higher operability values are related to islands and wetlands only accessible by boat. The accessibilities to the shoreline are mainly through concrete road.



SOURCES: NOAA, ICNB, CAOP2012, IGNE, INSAAR, NATURDATA, IGESPAR, ARH-Centro, IGP, PIORIA, POLIS, POOC-OMG, ADAPTARIA, APA, DGOTDU, F:ACTS!, Bing Maps, Maratec (2007), Vijayan, et al. (2009), Castañedo, et al. (2009)

Figure 2. The Ria de Aveiro case study area with the Port of Aveiro jurisdiction zone in detail; **a)** Environmental Sensitivity Map; **b)** Global Vulnerability Index; **c)** Access and Operability Index.

CONCLUDING REMARKS

Despite the preliminary character of this multi -approach, the included maps are important tools to support oil spill prevention and response mechanisms in Ria de Aveiro and similar case studies. They contribute to represent the actual state and exposure to oil spills events.

The simultaneous display of this multi-method approach shows differences in terms of the spatial distribution of each index. In this way, areas associated to high levels of sensitivity, are not necessarily the most vulnerable ones, and vice versa. Likewise, homogeneous sensitivity shoreline segments may relate to high variable vulnerability scores, or the other way around.

This study, also demonstrates that within coastal lagoons, impacts of oil spills can be different from place to place, contradicting overall generalizations assumed in other methodologies.

One of the main challenges remains to display the most relevant information, providing an easy read-out experience to end users.

The presented methodologies are being tested in other areas inside the Aveiro lagoon and their application in similar study areas is recommended. Other developments are being considered, including the integration of current and tidal energy, as additional physical dispersion factors.

Current methodologies should be refined to attenuate recurrent limitations and more recent methods must be studied and tested. The geodatabase should be updated as necessary, as the lagoon and region of Aveiro face continuous changes.

The work in oil spill assessment must be continued in a multidisciplinary way, in a sharing knowledge perspective, involving scientific community, civil protection, port authorities, the public and local economic agents.

ACKNOWLEDGEMENT

The European Union, under the European Regional Development Fund and INTERREG IV B: Atlantic Area Transnational Programme, supported this study through the collaborative research project SPRES (SPRES-2011-1/168). The Portuguese Foundation for Science and Technology (FCT) also supported this study through the research project PAC:MAN (PTDC/AAC-AMB/113469/2009), co-funded by COMPETE/QREN/UE.

LITERATURE CITED

Andrade, M. M., et al., 2010. A socioeconomic and natural vulnerability index for oil spills in an Amazonian harbour: a case study using GIS and remote sensing. *Journal of Environmental Management*, 91(10): 1972-1980.

Castañedo, S., et al., 2009. Oil spill vulnerability assessment integrating physical, biological and socio-economical aspects: Application to the Cantabrian coast (Bay of Biscay, Spain). *Journal of Environmental Management*, 91(1): 149-159.

EPA, 1999. Chapter 8 - Response to oil spills. In Oil Programme Center - EPA Office of Emergency and Remedial Response (eds): *Understanding oil spills and oil spill response - understanding oil spills in freshwater environments.* EPA, Washington D.C., USA. pp.37-44.

ESPON, 2003. Environmental hazards and risk management – thematic study of INTERREG and ESPON activities. European Union IINTERact, Technical Report, Luxembourg, Luxembourg. 53p.

Guzzetti, F., 2005. Landslide hazard and risk assessment. Ph.D.-thesis, Friedrich-Wilhelms-Univestität Bonn, Bonn, Germany. 373p.

Hayes, M. O., et al., 1997. The reach sensitivity index (RSI) for mapping rivers and streams. Proceedings of the International Oil Spill Conference, Fort Lauderdale, Florida, USA. pp. 343-350.

IPCC, 2001. Climate Change 2001: working group II: impacts, adaptation and vulnerability. Contribution of working group II to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Technical Report, Cambridge, UK. 1032p.

ITOPF, 2002. Fate of marine oil spills 2002. Technical information paper. The International Tanker Owners Pollution Federation Limited, Technical Report, London, UK. 12p.

ITOPF, 2012. Oil tanker spill statistics 2011. The International Tanker Owners Pollution Federation Limited, Technical Report, London, UK. 12p.

Kumpulainen, S., 2006. Vulnerability concepts in hazard and risk assessment. *Geological Survey of Finland Special Paper* 42: 65-74.

Leal, T. A. M., 2011. Sensibilidade costeira para planeamento e resposta a emergências de poluição marítima causada por hidrocarbonetos. MSc Thesis, Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa, Lisboa, Portugal. 167p.

MARETEC, 2007. Atlas Costeiro de Portugal Continental. Emergency Response to Coastal Oil, Instituto Superior Técnico, Erocips, Hidromod, Ciimar, Technical Report, Porto, Portugal. 19p.

MAOT & INAG, 2011. Revisão do Plano de Ordenamento da Orla Costeira Ovar - Marinha Grande, Fase 1: Relatório 2, Volume I – Caracterização e Diagnóstico Prospetivo. Ministério do Ambiente e Ordenamento do Território, Instituto da Água I.P., Technical Report, Lisboa, Portugal. 644p.

Ng, T. F., et al., 2008. Assessment of oil spill vulnerability of Southwest Pulau Pinang shoreline. *Bulletin of the Geological Society of Malaysia* 54: 123-131.

NOAA, 2002. *Environmental Sensitivity Index Guidelines Version 3.0.* NOAA Technical Memorandum NOS OR&R 11, Seattle, Washington, USA. 192p.

O'Sullivan, A. J. & Jacques, T.G., 1998. *Impact Reference System - Effects of Oil in the Marine Environment: Impact of Hydrocarbons on Fauna and Flora*. Community Information System for the Control and Reduction of Pollution.Productivity Commission, Brussels, Belgium. 87p.

Pincinato, F. L., et al., 2009. Modelling an expert GIS system based on knowledge to evaluate oil spill environmental sensitivity. *Ocean & Coastal Management* 52(9): 479-486.

Pio, S. & Henriques, A. G., 2000. O estado ecológico como critério para a gestão sustentável das águas de superfície. Proceedings of the Congresso da Água 2000, Lisboa, Portugal: pp. 1-15.

Santos, C. F. & Andrade, F., 2009. Coastal Sensitivity Assessment in Portugal. *Journal of Coastal Research* (SI 56): 885-889.

Santos, C. F., et al., 2012. Quantitative assessment of the differential coastal vulnerability associated to oil spills. *Journal of Coastal Conservation*. (Published online: 12 September 2012)

Vafai, F., et al., 2013. Determination of shoreline sensitivity to oil spills by use of GIS and fuzzy model. Case study – The coastal areas of Caspian Sea in north of Iran. *Ocean & Coastal Management* 71: 123-130.

Vaz, N., et al., 2005. Dynamics of a temperate fluvial estuary in early winter. *Global NEST Journal,* 7: 3, 237-243.

White, I. C., 2002. Factors affecting the cost of oil spills. GAOCMAO Conference, Muscat, Oman, 12-14 May 2002. ITOPF, London. 9p.

Zêzere, J. L., 2011. Landslide susceptibility and landslide hazard in coastal slopes. Coastal hazard assessment and risk management FORM-OSE Post-graduate Training School, 19-25 June 2011. University of Caen Basse-Normandie, Presentation, Caen, France. 68p.