Journal of Environmental Management 91 (2009) 149–159

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Oil spill vulnerability assessment integrating physical, biological and socio-economical aspects: Application to the Cantabrian coast (Bay of Biscay, Spain)

S. Castanedo*, J.A. Juanes, R. Medina, A. Puente, F. Fernandez, M. Olabarrieta, C. Pombo

Environmental Hydraulics Institute, IH Cantabria, Universidad de Cantabria, Av. de los Castros s/n, 39005 Santander, Spain

ARTICLE INFO

Article history:
Received 7 January 2009
Received in revised form
9 July 2009
Accepted 28 July 2009
Available online 6 September 2009

Keywords:
Vulnerability index
Physical index
Biological index
Socio-economical index
Oil spill
GIS
Coastal management

ABSTRACT

A methodology has been developed to carry out an integrated oil spill vulnerability index, V, for coastal environments. This index takes into account the main physical, biological and socio-economical characteristics by means of three intermediate indexes. Three different integration methods (worst-case, average and survey-based) along with ESI-based vulnerability scores, V_{ESI}, proposed for the Cantabrian coast during the *Prestige* oil spill, have been analyzed and compared in terms of agreement between the classifications obtained with each one for this coastal area. Results of this study indicate that the use of the worst-case index, V_R, leads to a conservative ranking, with a very poor discrimination which is not helpful in coastal oil spill risk management. Due to the homogeneity of this coastal stretch, the rest of the methods, V_I, V_M and V_{ESI}, provide similar classifications. However, V_M and V_I give more flexibility allowing three indexes for each coastal segment and including socio-economic aspects. Finally, the V_I procedure is proposed here as the more advisable as using this index promotes the public participation that is a key element in the implementation of Integrated Coastal Zone Management (IZCM).

1. Introduction

In order to respond quickly and successfully to an oil spill in a defined geographical area, a contingency plan including information and processes for oil spill containment and clean-up is required. An important part of the plan's development should involve the risk assessment which, on top of evaluating the oil spill probability for a specific area, must determinate the coastal environments that would be most seriously damaged by an oil spill or, in other words, the vulnerability. On the basis of this information, protection strategies could be designed. The assessment of the oil spill vulnerability of coastal environments is a fundamental issue when planning an oil spill response as it is one of the key components of the risk determination.

One of the earlier attempts to estimate coastal oil spill vulnerability can be found in Gundlach and Hayes (1978) where a classification of coastal environments based on their physical and geological characteristics is presented. More recently, NOAA (Petersen et al., 2002) developed the *Environmental Sensitivity Index (ESI) maps*, in which not only physical features, but also biological information and human use of the shoreline are included. Based on this work, a GIS-based ESI classification of the Cantabrian shoreline (North of Spain) was undertaken within the framework of the Emergency Spill Response System (ESRS) implemented by the Regional Government and the University of Cantabria to mitigate the impact of the *Prestige* oil spill (Juanes et al., 2007).

Other works also focusing on the estimation of an environmental sensitivity index to oil spills are Hanna (1995) in the Egyptian Red Sea coastal area, Nansingh and Jurawan (1999) in the Trinidad (West Indies) coastline, Adler and Inbar (2007) in the Mediterranean coast of Israel and Wieczorek et al. (2007) in the state of Sao Paulo (Brazil), among others. Some recent examples can also be found in Europe. In France, CEDRE (Centre of Documentation, Research and Experimentation on Accidental Water Pollution) is leading the development of an oil spill *Sensitivity Atlas for the Finisterre* region (Michel Girin, personal communication). This atlas is structured into three main layers based on physical, biological and economical features related to the coast. In Denmark, the National Environmental Research Institute has developed the *Environmental Oil Spill Sensitivity Atlas* covering West Greenland which provides an overview of such aspects as the existence of wildlife, human resource usage and archaeological sites that are particularly sensitive to oil spills (http://www.dmu.dk/International/Arctic/Oil/Sensitivity+Atlas/).

* Corresponding author. Tel.: +34 942 201852; fax: +34 942 201860.
E-mail address: castanedos@unican.es (S. Castanedo).

0301-4797/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jenvman.2009.07.013

Usually, the physical analysis assesses the potential impact of an oil spill based on the oil persistence on the coast. Previous works investigated the relative importance of several factors to the littoral self-cleaning capacity (Michel et al., 1978; Tsouk et al., 1985). In these studies, the effects on the oil persistence of the sedimentological composition of the beaches and the related wave energy characteristics and processes were examined. The conclusion was that the beach profile and factors determining the coast exposure to wave action were of primary importance.

Biological aspects aim to measure the ecological impacts of an oil spill. Although each spill event can be considered a unique blend of place, oil properties, nature and human influences, current knowledge on oil fate and effects allows us to understand and anticipate likely impacts and predict recovery (O'Sullivan and Jacques, 2001; Hayes et al., 1992; Sloan, 1999). Furthermore, the numerous oil disasters that took place in the 90s have provided a continuous experimental ground to improve assessment procedures and to validate hypotheses on environmental damage (e.g. Guven et al., 1998; Peterson, 2000; Gelin et al., 2003; French, 2004; Gomez Gesteira et al., 2003; Zenetos et al., 2004; Juanes et al., 2007). Nevertheless, the ecological impact of a specific oil spill should integrate the aforementioned valuable information regarding the intrinsic sensitivity of different coastal areas, species and communities inhabiting the aquatic ecosystem with the local singularities (health status, degree of exposure to the oil spill or the resilience).

When considering the economic aspect of vulnerability, the assessment of the socio-economic cost derived from accidental oil spills is a challenge for the economic science. Usually, private cost and collective damages are considered into the cost valuation. However, disasters also cause non-commercial damages that cannot be easily priced, for example, those related to the recreational use of the natural areas (Garcia Negro et al., 2007). A number of studies based on traditional economic analysis as well as on new methodologies, such as the Habitat Equivalency Analysis (HEA), have explored this subject (e.g. Preston et al., 1990; Brown, 1992; Cohen, 1995; Dunford et al., 2004; Roach and Wade, 2006). More specifically, there are published works mainly related to the economical effects of the *Prestige* oil spill in the NW coast of Spain (Garza-Gil et al., 2006; Loureiro et al., 2006; Wirtz and Liu, 2006; Garcia Negro et al., 2007). Advances in these studies are crucial for many reasons, the compensation purpose being one of the most relevant issues. However, as highlighted by many of the above-mentioned authors, the outreach of these economic analyses is usually limited by the lack of solid statistical data regarding the losses in the productive sectors.

Most of the aforementioned vulnerability studies provide their results by means of static atlas (paper maps) which show in separate sheets the information regarding physical, biological and economics aspects of the shoreline related to oil spill impact. This may complicate the consideration of dynamic aspects related to biological and socio-economic elements (e.g. seasonal patterns, temporary activities). Although in Spain, GIS (Geographical Information Systems) based mapping is not mandatory, these technologies can provide an important tool for the management and constant update of the different types of data required for the assessment of vulnerability.

In spite of the specific advances in the separate assessment of each element, the consideration of all these factors as a whole would be highly desirable to facilitate the oil spill response planning. Consequently, this paper develops a methodology to determine an integrated index which represents the "global" oil spill vulnerability of a coast. In order to provide a useful decision-making tool, special emphasis is given to integration of physical, biological and socio-economical aspects into one single index, using the Cantabrian coast (North of Spain, Gulf of Biscay), one of the most affected areas during the Prestige oil spill (Castanedo et al., 2006; Juanes et al., 2007), as the field-ground for validation of the new proposal.

2. Material and methods

2.1. Study area and assessment units

The area of interest is the Cantabrian coast, located on the Northern coast of Spain (Bay of Biscay) (Fig. 1), included within the Biogeographic Region of the NE Atlantic. Regarding the wave climate, the most energetic and frequent waves come from the northwest sector, with a mean significant wave height, H_s, of 1 m and a typical winter storm wave of $H_s \approx 5$ m. Northeast waves are shorter and less frequent (usually in summer). Waves from NW, N and NE approach with a period between 12–20 s, 7–15 s and 4–8 s, respectively. Tide is semidiurnal with a mean and spring tide range of 3 and 5 m, respectively.

The Cantabrian coast is divided into a series of pocket beaches and small inlets isolated between rocky headlands. Considering structural and functional points of view, three types of environmental units have been distinguished: estuaries, rocky shores and sandy beaches. The analysis carried out covered 14 estuaries and 200 km of rocky shores and sandy beaches, including five different Special Areas for Conservation (SAC) integrated within the European Nature 2000 network covering approximately 50% of the shoreline.

In order to apply an oil spill vulnerability index to the coast, assessment units or coastal segments have been established. The length, L, of the assessment units has been selected taking into consideration the geomorphologic homogeneity of the entire section. On the other hand, the chosen length had to be realistic to facilitate database management. Considering these premises and based on detailed analyses of the Cantabria shoreline characteristics carried out during the *Prestige* oil spill impact assessment (FLTQ, 2006), shoreline segments of 200 m length, L, were selected (1237 coastal segments) (Fig. 1). Following the methodology that is presented in the next sections, physical, biological and economic data were obtained for each unit. A GIS-based on 1:5000-scale aerial photography and a digital elevation model of 5×5 m resolution, provided the detailed information and the physical support for their spatial delimitation. Estuarine features were associated to the shoreline segments located along the tidal inlets.

2.2. Vulnerability index

Three intermediate indexes, representing the physical, I_P, biological, I_B, and socio-economical, I_E, coastal characteristics, have been defined and calculated for the vulnerability assessment of each shoreline segment. The results obtained at those units were then integrated following four methodological procedures as shown here:

a. The worst-case vulnerability of a segment, V_R, is assigned on the basis of the value corresponding to the most restrictive score of the intermediate indexes (I_P, I_B, I_E).
b. The average vulnerability of a segment, V_M, is calculated as the arithmetic mean of the values of the intermediate indexes.
c. The integrated vulnerability index, V_I, is calculated by means of the following expression

$$V_I = I_P V_0 \quad (1)$$

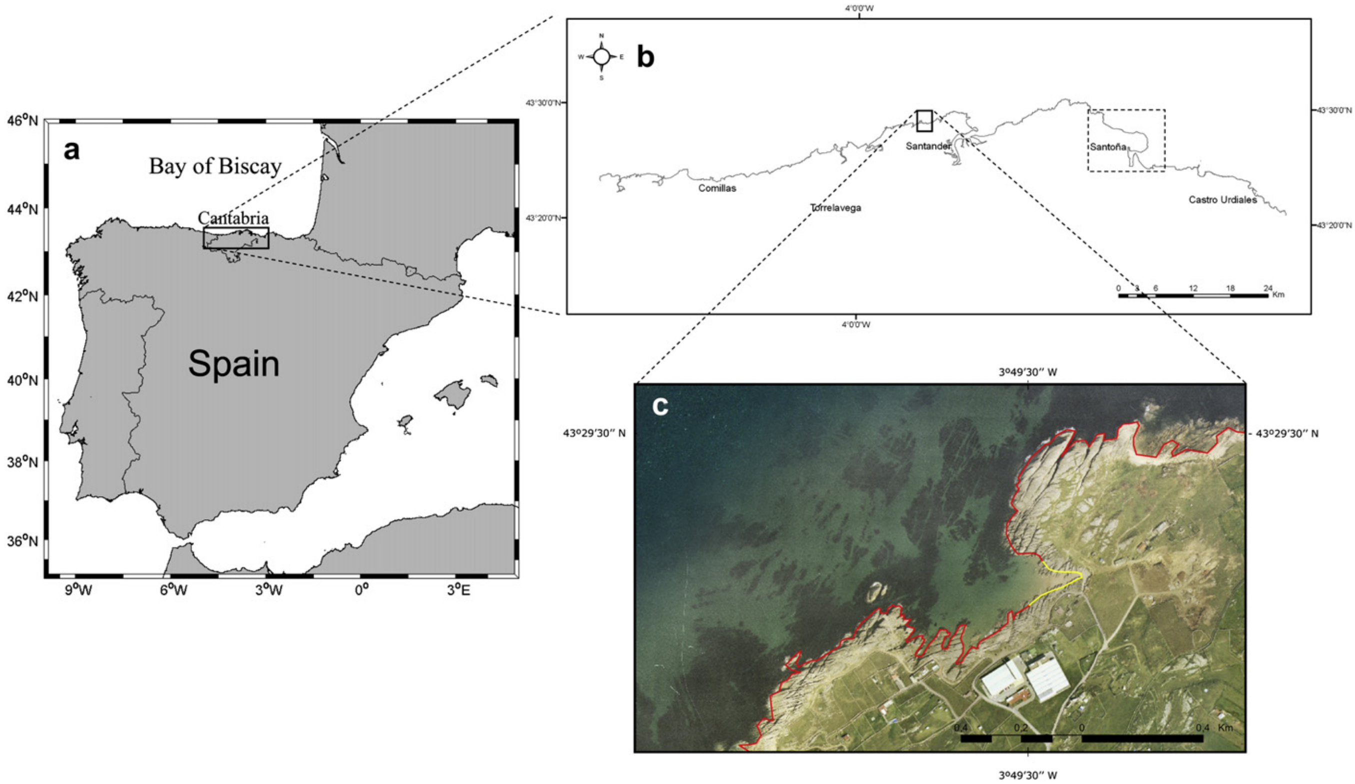

Fig. 1. (a) Location map of the coast of Cantabria; (b) studied shoreline (the dashed rectangle shows the location of the image from Fig. 4); (c) shoreline (red) and example of assessment unit (yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

where I_P is the physical index and V_0 is expressed as a joint function of the biological, I_B, and the socio-economical indexes, I_E:

$$V_0 = f(I_B, I_E) \tag{2}$$

where the function f is calculated as

$$f(x,y) = a_1 I_B^{b_1} + a_2 I_E^{b_2} \tag{3}$$

provided

$$f = 0 \quad \text{if} \quad I_B = I_E = 0 \quad \text{and}$$

$$f = 1 \quad \text{if} \quad I_B = I_E = 1$$

where f, I_B and I_E are normalized values (0–1).

After applying the restrictions established in Eq. (3), the final model stands as

$$V_0 = rI_B^{b_1} + (1-r)I_E^{b_2} \tag{4}$$

The parameters, r, b_1 and b_2, for the study area, were determined by means of a Delphi survey taking into account the participation of different stakeholders. Following the recommendation of the European Parliament and the Council (OJEC, 2002) and adapting it to oil spill response management, a survey was distributed between agents belonging to the following socio-economic sectors: fisheries and aquaculture, resource management, species and habitat protection, tourism, recreation and research institutions.

d. Vulnerability scores, assigned by the modified version of the ESI proposed by Juanes et al. (2007) for this coastal area, were also considered for each assessment unit (V_{ESI}).

The three intermediate indexes (I_P, I_B, I_E) were calculated as described in the following.

2.2.1. Physical index

The physical index, I_P, assesses the potential impact of an oil spill based on the self-cleaning capacity of each coastal segment, depending on its wave exposure, E, and its mean shoreline slope, SP:

$$I_P = E + \mathrm{SP} = O + S + \mathrm{SP} \tag{5}$$

where E is calculated as the arithmetic sum of the orientation, O, and the sinuosity, S, of the assessment unit.

The orientation factor, O, takes into account the wave energy beating the coast. In order to evaluate the orientation of a coastal segment, we calculated the azimuth of each orientation line (straight lines that join the start and the end points of each coastal segment) and we applied the following scale obtained from the analysis of the wave climate of the study area: shoreline sections whose orientation lines are oriented to the dominant waves (azimuth between 225° (SW) and 22.5° (NNE)) are given a score of 1, those oriented to waves from NNE–E sector (azimuth 22.5°–90°) 2, and the rest, E–SW, (azimuth 90°–225°) 3 on the scale. The higher the score, the more protected the analyzed area is, the slower the self-cleaning process. Wave climate was calculated using the SIMAR-44 hindcast database generated by Puertos del Estado (Ratsimandresy et al., 2008).

The sinuosity parameter acts as a correction of the orientation indicator: zones with more sinuosity present irregularities where oil could persist despite high wave energy. The sinuosity, S, of each shoreline segment has been calculated using the following relation:

$$S = l/L \tag{6}$$

where L is the shoreline segment length (= 200 m) and l is the length of the orientation line for this segment. Note that for straight shoreline sections, the value of S will approximate 1. On the other hand, the more sinuous a segment is, the lower the value of S will be (1: 1–0.85; 2: 0.85–0.6; 3: 0.6–0). The sum of the orientation and sinuosity scores gives an exposure score, E, which has been grouped as shown in Table 1. Exposed shoreline sections receive high wave energy and have a low sinuosity. On the contrary, sheltered areas are mainly protected from the most energetic waves and they also have a high sinuosity producing a higher oil residence time.

The shoreline slope, SP, is a key factor regarding the oil persistence in the coast. Areas with a gentle slope will more easily retain the oil than those which are steeper. Based on the experience acquired during the *Prestige* oil spill cleaning-up operations, the mean slope associated to the swash process in high tide was adopted as an adequate indicator. In order to determine the vertical limits of this zone (flooding level) the effects of the astronomical tide, storm surge and wave run-up, were considered.

Based on sea level data from the Santander tidal gauge, the sea level (tide + storm surge) cumulative distribution function was calculated and the 90th percentile sea level was obtained. With regards to the wave run-up, two formulations depending on the shoreline slope were used. For smooth slopes ($SP \le 1/10$) Holman's (1986) relation was applied

$$R_{2\%} = 0.9H_s \tag{7}$$

For intermediate ($1/10 < SP < 1/2$) and steep ($SP \ge 1/2$) slopes, the following equation (Van der Meer, 1993) was used.

$$R_{2\%} = 2 \div 3H_s \tag{8}$$

In the above expressions $R_{2\%}$ is the run-up that only two percent of the wave run-up values observed will reach or exceed, and H_s is the significant wave height considered in this study. Here, the 95th percentile H_s has been taken as representative. To obtain this value, wave data from a nearby deep-water buoy (Bilbao buoy) was used.

According to these values and applying Eqs. (7) and (8), the vertical limits of the zone where the shoreline slope should be calculated were established. Depending on its slope, each shoreline segment was included in one of the three groups determined by the following scale: 1: $SP > 1/2$ (steep); 2: $1/10 < SP < 1/2$ (intermediate); 3: $SP < 1/10$ (smooth). The shoreline environments included in each slope type were: 1: rocky cliffs with steep slope; 2: rocky cliffs with intermediate slope; cliffs with cobble- or boulder-size rock fragments at the base; accumulation areas of boulder-size material; 3: beaches; wave-cut platforms in bedrock.

Regarding the substrate permeability, previous analysis (FLTQ, 2006) demonstrated that it is implicitly included in the slope parameter. Steep shoreline sections present an impermeable behaviour for the oil, while flatter sections usually act like permeable surfaces. Exposed wave-cut platforms in bedrock are the exception of this rule. These flat environments have impermeable substrate and oil will not adhere to the rock platform. In this study, this exceptionality is assumed and it is addressed later on in the cleaning cost parameter where the type of substrate is taken into account.

To obtain the physical scaling, Eq. (5) was applied. The wave exposure, E, was considered to be predominant over the shoreline slope, SP, in terms of the self-cleaning capacity of a shoreline sector. Table 2 gives the proposed scale for the I_P.

The above procedure is not applied to estuaries. These environments are composed primarily of soft bottoms. Oil adheres rapidly to high intertidal level vegetation and cleaning these areas is very difficult. On the other hand, the self-cleaning capacity of the estuaries is very low and, consequently, they were given the maximum value for the exposure and slope indicators to reach an $I_P = 10$, becoming the most vulnerable areas from a physical point of view.

2.2.2. Biological index

The biological index, I_B, was designed to assess the environmental vulnerability associated to oil spills. To this effect, three general indicators have been proposed to estimate homogeneously the specific I_B indexes for the established types of coastal environments (estuaries, beaches and coastal rocky zones). The conservation state, I_c, takes into account the current structural and functional status of the water body in which each segment is included. The singularity value, I_s, considers the value for conservation of the segment, according to its legal protection status. Finally, the resilience factor, I_r, shows the power of the community to recover following the perturbation caused by an oil spill and the speed with which it is able to do so.

Evaluation of these indicators is carried out using specific criteria for the segments assigned to each coastal type. I_c estimates of segments corresponding to estuarine water masses are based on "ecological status" assessments, sensu Water Framework Directive 2000/60/CE, while the structural complexity of coastal dunes (i.e. existence of primary, secondary or tertiary dunes) and the presence/absence of waste water discharges on the shoreline are the selected feature in the case of dunes and rocky shores, respectively (Table 3).

On the other hand, a more homogeneous criteria has been selected for singularity estimates, I_s, of all the coastal types, based on legal declarations of conservation values at local (i.e. protected landscapes, regional parks), national (i.e. natural parks) or international levels (i.e. Ramsar sites, European Sites of Interest for Conservation) (Table 3). Special concern is dedicated to small island spaces in the case of the rocky coast.

Table 1
Exposure scale.

Orientation score	Sinuosity score	Total score	Exposure
1	1		1 (Exposed)
1	2	≤ 3	
2	1		
1	3		2 (Semi-exposed)
2	2	=4	
3	1		
2	3		3 (Sheltered)
3	2	≥ 5	
3	3		

It is calculated grouping into three categories the arithmetic sum of the orientation, O, and sinuosity, S, parameters.

Table 2
Physical index, I_P.

Exposure	Shoreline slope	Total score	I_P
1 (Exposed)	1 (Steep)	2	1
1 (Exposed)	2 (Intermediate)	3	2
2 (Semi-exposed)	1 (Steep)	3	3
1 (Exposed)	3 (Smooth)	4	4
2 (Semi-exposed)	2 (Intermediate)	4	5
3 (Sheltered)	1 (Steep)	4	6
2 (Semi-exposed)	3 (Smooth)	5	7
3 (Sheltered)	2 (Intermediate)	5	8
3 (Sheltered)	3 (Smooth)	6	9
4 (Estuary)	4 (Estuary)	8	10

The total score is calculated as the arithmetic sum of the exposure, E, and the slope, SP, parameters. The I_P scaling is obtained ranking the total score into ten classes assuming E to be predominant over SP regarding coast self-cleaning capacity.

Table 3
Summary of corresponding score values of biological indicators (I_c, I_s, I_r) for different environmental conditions of the three coastal segment types (estuaries, beaches and rocky areas).

	Score	Estuaries	Beaches	Rocky areas
Conservation state (I_c)	0	Ecol. state: very bad	No vegetation	Industrial discharges
	1	Ecol. state: bad	Primary dunes	Raw urban discharges
	2	Ecol. state: moderate	Secondary dunes	Treated urban effluent
	3	Ecol. state: good or high	Tertiary dunes	No discharges
Singularity (I_s)	0	No legal protection		
	1	Protected landscapes, Fisheries reserves		
	2	Nature reserves, Important Bird Areas (IBA)		
	3	Marine Reserves and Natural Parks		
	4	European Natura Network Areas, National Parks, Reserves of Biosphere		
Resilience (I_r)	0	No vegetation	No dune	Vertical clifts
	1	Sv < 100 ha and $C < 50\%$ or Sv < 500 ha and $C < 35\%$	Lpd < 25%	High slope areas
	2	Sv > 500 ha and $C < 35\%$ or Sv < 100 ha anf $C > 50\%$ or Sv: 100–500 ha and C: 35–50%	Lpd 25–75%	High slope areas with boulders and cobbles/Median slope areas
	3	Sv > 100 ha and $C > 35\%$ or Sv > 500 ha and $C > 35\%$	Lpd > 75%	Median slope areas with boulders and cobbles/Low slope areas

Sv: Intertidal vegetated surface in hectares (ha); C: Relative cover of vegetation (%); Lpd: Relative length of the beach with primary dunes.

Finally, the third indicator, the resilience factor, I_r, uses three different approaches for each coastal type (Table 3). In the case of estuarine habitats, this factor is estimated by quantification of the percentage of vegetated surfaces within the intertidal areas, weighting the scores according to the total intertidal size of each estuary. Oppositely, the I_r of coastal dunes is assessed in terms of percentage of length of the sandy area that is currently vegetated. Finally physical criteria, the intertidal slope together with the presence of boulders and cobblestones, are taken into consideration for resilience estimations in rocky shores.

2.2.3. Socio-economic index

The socio-economic index, I_E, estimates the economic damage assigned to each shoreline segment, i, ($€_i$) in terms of income losses resulting from interrupting activities related to the coastal uses together with the cleaning cost, $€_c$. The economic damage (in €), was estimated as:

$$€_i = €_j + €_c \tag{9}$$

where $€_j$, stands for the global economic loss associated to each of the five activities considered in the present study ($j = 1$ fishery; $j = 2$ shellfish; $j = 3$ tourism; $j = 4$ harbour activity; $j = 5$ recreation) calculated here as:

$$€_j = \left[\left(€_j^g/\text{month}\right)K_s\right](I_d \times R_t) \tag{10}$$

where $€_j^g$ stands for the monthly generated income for each activity j; K_s is a seasonality coefficient obtained from the Statistic Institute of Cantabria (www.icane.es); I_d is the impact degree that takes into account the percent of the activity income affected by the oil spill and R_t is the recovery time, defined as the time (months) that an activity requires to return to a normal situation. Specific I_d (%) and R_t (months) values for a *Prestige* fuel type (heavy fuel No. 6) have been developed for each activity, j, using actual data from the oil spill response managers ($j = 1$: $I_d = 100$, $R_t = 4$; $j = 2$: $I_d = 100$, $R_t = 12$; $j = 3$: $I_d = 10$, $R_t = 6$; $j = 4$: $I_d = 80$, $R_t = 0.25$; $j = 5$: $I_d = 100$, $R_t = 0.25$). The application of Eq. (10) to each activity is presented in Table 4.

Total landings of main inshore (sardine, horse mackerel and hake) and off-shore fish species (blue mackerel, blue fin tuna and anchovy) in each port during 2001–2002 (Statistic Institute of Cantabria) were valued according to mean fresh market price for each species to estimate $€^g_{\text{fishery}}$. Inshore species were equally assigned to each shoreline segment. Meanwhile for off-shore species, losses were assigned only to those segments included in the area of influence of each port. A similar approach was applied to estimate the $€^g_{\text{shellfish}}$, regarding total shellfish captures in each extraction area between 2002 and 2004 (clam, goose barnacle, razor clams and bait). Further economic losses for inland aquaculture activities have also been taken into account.

$€^g_{\text{tourism}}$ estimates were based on average daily expenditures per traveller (Deloitte and Exceltur, 2005) in different types of lodging establishments (hotel, apartment, second house, camping). General tourism areas were established along the coastline and the resulting $€^g_{\text{tourism}}$ values were split between the estuarine and beach segments (75%) and the rocky shores (25%).

Regarding the $€_{\text{harbour}}$, it was assessed from data provided by the only commercial facility in the region, the Port of Santander.

Table 4
Expressions to estimate the income losses resulting from interrupting activities related to the coast uses.

Activity	Economic loss
Fishery	$€_{\text{fishery}} = [\sum_{i=1}^{N}(€^g_{\text{IS}_i}\cdot K_{s,i}) + \sum_{i=1}^{M}(€^g_{\text{OS}_i}\cdot K_{s,i})](I_d \times R_t)$ N, M: number of inshore and off-shore species respectively $€^g_{\text{IS}_i}$: monthly generated income for the inshore specie i $€^g_{\text{OS}_i}$: monthly generated income for the off-shore specie i $K_{s,i}$: seasonality coefficient for specie i
Shellfish	$€_{\text{shellfish}} = [\sum_{i=1}^{N}(€^g_{s_i}\cdot K_{s,i}) + (€^g_{\text{aq}}\cdot K_{s,\text{aq}})](I_d \times R_t)$ N: number of shellfish species considered in the study $€^g_{s_i}$: monthly generated income for extracting the shellfish specie i $€^g_{\text{aq}}$: monthly generated income for the aquaculture activity $K_{s,i}$: seasonality coefficient for specie i $K_{s,\text{aq}}$: seasonality coefficient for the aquaculture
Tourism	$€_{\text{tourism}} = \sum_{i=1}^{N}[(€^g_{\text{night},i}R_i)K_{s,i}](I_d \times R_t)$ N: types of lodging establishments considered in the study (1 = hotel, 2 = apartment, 3 = second house, 4 = camping) $€^g_{\text{night},i}$: monthly generated income per person/night in an establishment type i R_i: monthly rooms in a lodging establishment type i.
Harbour activity	$€_{\text{harbour}} = \epsilon(I_d \times R_t)$ ϵ: are the monthly losses (in euros) resulting from interrupting the port activity (25 days of damage)
Recreation	$€_{\text{recreation}} = [(€^g_{\text{surfing}} + €^g_{\text{diving}} + €^g_{\text{sailing}}) + (N€_{\text{mooring}})]K_s \times I_d \times R_t$ $€^g_{\text{surfing}}$, $€^g_{\text{diving}}$, $€^g_{\text{sailing}}$: monthly generated income for the surfing, diving and sailing activities respectively. N: number of moorings $€_{\text{mooring}}$: monthly average cost per mooring

Finally, $€_{recreation}$ was estimated using data from sailing, diving, surfing and marina activities provided by 30 clubs and schools, and it was assigned to shoreline segments on a usage basis (e.g. surfing: beaches; sailing: marinas; diving: coastal stretch).

On the other hand, the clean-up cost, $€_c$, was estimated using the following expression

$$€_c = C(BL) \tag{11}$$

where C is the clean-up cost ($€/m^2$) obtained using actual data from the Prestige oil spill clean-up (Spanish Ministry of Environment: Natural cleaning = 0; beach = 88; rocky substrate = 112; boulders = 161; estuary = 161); B is the affected cross-distance (width) carried out depending on the shoreline slope (Steep = 4; intermediate = 6; smooth = 10; estuaries = 10) and L is the assessment unit length or the estuary perimeter.

To obtain I_E, $€_i$ was divided into ten categories using Jenks' natural breaks classification to determine interval breaks (ESRI knowledgebase).

2.2.4. Exploring different integration methods to obtain a vulnerability index

To achieve the main goal of this work, namely, to provide the decision-makers with a useful oil spill response management tool, the results of applying the proposed vulnerability expressions (V_I, V_R, V_M and V_{ESI}) to the Cantabrian coast have been analyzed. This analysis has mainly focussed on answering questions such as: How dissimilar are the rankings obtained from each method? Is any approach more advisable than the others? Which method is the most conservative? Does any approach stress the importance of some of the three considered aspects of the coast (physical, biological and economical)?

To evaluate the difference between the coastal classifications given by these oil spill vulnerability indexes, the kappa coefficient of agreement (Cohen, 1960) was calculated:

$$\kappa = \frac{p_0 - p_e}{1 - p_e} \tag{12}$$

where p_0 $(=\sum_{i=1}^{c} p_{ii})$ is the overall proportion of observed agreement (main diagonal of the matrix); p_{ii} are the proportions of observed agreements between the two methods for each category, c, and p_e $(=\sum_{i=1}^{c} p_{i.}p_{.i})$ is the overall proportion of chance-expected agreement (dot notation indicates marginal totals).

In order to take into account the level of disagreement, the weighted kappa coefficient, κ_w, was used incorporating an a priori assignment of weights to each of the cells of the table. The selection of weights was done following Fleiss and Cohen (1973),

$$w_{ij} = 1 - \frac{(i-j)^2}{(c-1)^2} \tag{13}$$

were i and j are the ith column and the jth row of the weights matrix respectively. Using Eq. (13), the coefficients p_0 and p_e will be modified as

$$p_{0(w)} = \sum_{i=1}^{c}\sum_{j=1}^{c} w_{ij}p_{ij}, \quad p_{e(w)} = \sum_{i=1}^{c}\sum_{j=1}^{c} w_{ij}p_{i.}p_{.j} \tag{14}$$

To make the kappa analysis, the V_I index, based on the participation of stakeholders involved in the decision-making process, coast users and researchers, was assumed to be the more suitable approach to assess a "decision-maker" vulnerability index. It was therefore the control method which was compared with the others classifications. Besides this study, empirical probability density functions (empirical pdfs) of the different data obtained were used to draw some conclusions.

3. Results and discussion

All the data generated during the development of this work, as well as the results obtained, are managed using a GIS and a Relational Data Base Management System (RDBM). Besides this dynamic support, a static Atlas (hard-copy maps) for the Cantabrian coast, including the different indexes calculated, has been provided (Castanedo et al., 2008). Fig. 2a shows the calculated I_P, I_B, and I_E indexes for the whole Cantabrian coast.

The line that represents the physical index shows mainly blue colours, indicating that this coast does not present high oil spill vulnerability from a physical point of view. On the other hand, the higher vulnerability scores are found in the I_B index. To investigate in more detail all these aspects, the empirical pdfs of the three intermediate indexes have been undertaken (Fig. 2b–d).

Note that the pdfs corroborate the aspects indicated by the coloured lines in Fig. 2a. Almost 40% of the coastal segments present an I_P of 1 and 65% have an I_P less than 4. These values correspond to a steep coast, predominantly exposed to the wave energy (see Table 2). The most vulnerable areas, from a physical point of view, are practically confined to the estuaries (1.5%).

The I_B pdf displays two peaks of probability in the scores 4 and 8, representing 33% and 26% of the coastal segments, respectively. This behaviour can be explained through the intermediate indexes I_c, I_s and I_r that make up I_B. The analysis carried out (see Fig. 3) shows that most of the studied coast (80% of the assessment units) has a conservation index of 3, the highest score in the I_c scale (see Table 3). This is mainly due to the practically complete absence of waste water discharges on the shoreline in the rocky shores. Moreover, it can be seen that the most probable values for the I_s are 0 (50%) and 4 (44%). The later is due to the fact that almost all the protected areas in the Cantabrian coast (most estuaries and nearly 50% of the shoreline) belong to the European Natura 2000 Network Areas. On the other hand, the I_r index indicates that 70% of the coast presents a high resilience or capacity of recovering from an oil spill ($I_r = 1$). Note that combining all this information the most probable values of I_B are 4 and 8, as was mentioned above ($I_c = 3 + I_s = 0$ or $4 + I_r = 1$).

Returning to Fig. 2, it can be seen that the socio-economic index pdf has two peaks of probability in the scores 2 and 8. This means that the coast is mainly divided into two groups, one with a very low I_E (50%) and another with a high I_E (34%). Observing the I_E line in Fig. 2a, it can be appreciated that the first group ($I_E = 2$) is made up of coastal segments belonging to the rocky shore type and, on the other hand, the maximum I_E values correspond to the areas surrounding the estuaries. This fact reflects the high socio-economic value of these areas, which concentrate an elevated productivity related to all the economic activities considered (fishery, shellfish, tourism, harbour activity and recreation).

3.1. Calculation of V_I (integrated)

In order to combine the I_P, I_B, and I_E indexes to obtain a single value, V_I, the parameters r, b_1 and b_2, of Eq. (4) must be determined. This has been done by conducting a survey involving different institutions and groups related to the study area which gave 17 returns from the following sectors: National and Regional Environmental Ministries, National and Regional Agriculture and Fishing Ministries, Merchant Navy, Port Authority, Regional Chamber of Commerce, Industry and Shipping, Research

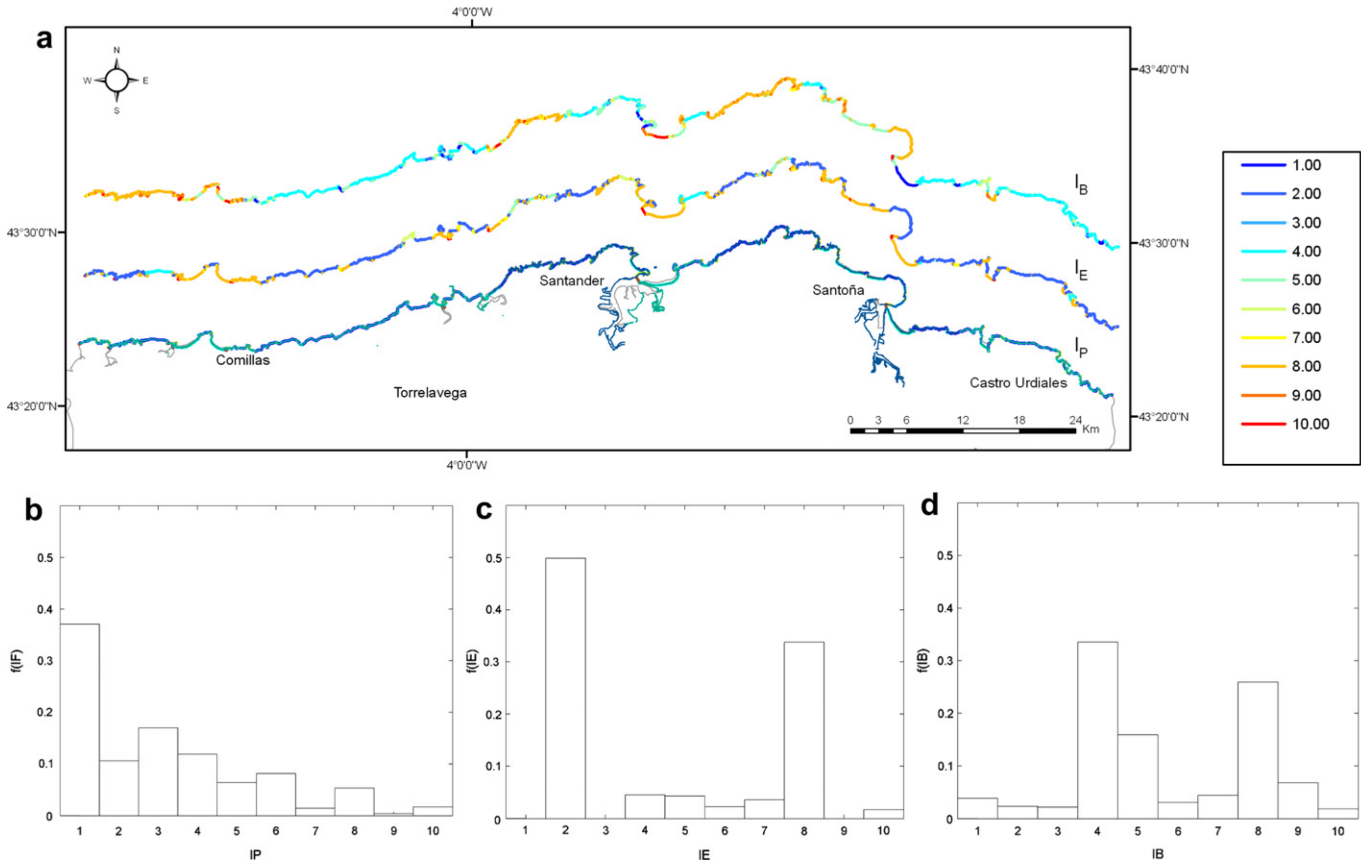

Fig. 2. (a) Representation of I_P, I_B, and I_E indexes for the whole Cantabrian coast; (b) empirical pdf for I_P; (c) empirical pdf for I_B; (d) empirical pdf for I_E.

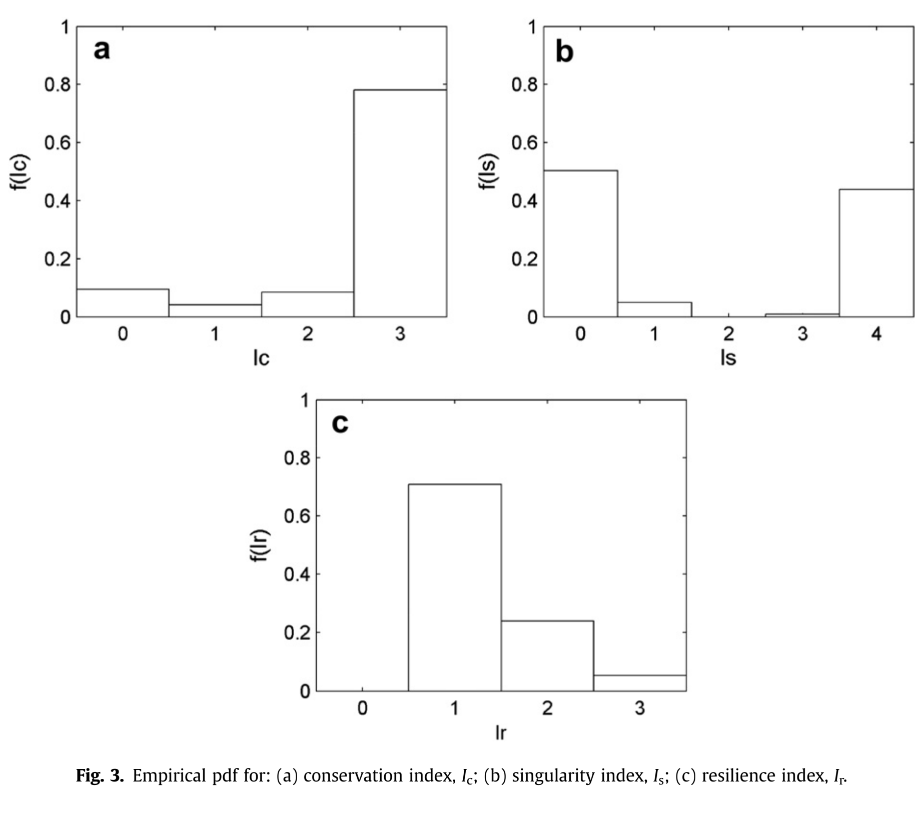

Fig. 3. Empirical pdf for: (a) conservation index, I_c; (b) singularity index, I_s; (c) resilience index, I_r.

Institutions, fisheries and shellfish representatives, coastal protected area managers, ecological groups and tourism business representatives.

The form consisted of twelve shoreline segments representing different types of environments from the physical, biological and socio-economic point of view. The survey aimed to rank these coastal environments depending on their oil spill vulnerability. The answers had to be based on the interviewee's opinion, experience and/or knowledge.

After analyzing the survey answers, the parameter estimates were obtained using a nonlinear least squares algorithm. The best fit model results were $r = 0.7$, $b_1 = 1$ and $b_2 = 4.4$. Finally, the expression to assign an integrated vulnerability index for a Cantabrian coastal segment was obtained:

$$V_{\mathrm{I}} = I_{\mathrm{p}}\left(0.7I_{\mathrm{B}} + 0.3I_{\mathrm{E}}^{4.4}\right) \tag{15}$$

3.2. Comparing the vulnerability indexes

The application of the methodology presented above, resulted in four vulnerability values for each one of the assessment units into which the Cantabrian coast was divided.

As an example, the classification given by V_{I}, V_{R}, V_{M} and V_{ESI} for the Santoña Estuary area (Northeastern coast of Cantabria), is illustrated in Fig. 4. In this area, there are assessment units belonging to the three types of previously defined coastal environments: estuaries, sandy beaches and rocky shores. Looking at the figure, it is possible to appreciate that the vulnerability values calculated by means of the four approaches are quite different. At first glance, the classification provided by the worst-case vulnerability index, V_{R}, is that which presents the greater differences with the rest. In this case, almost all the coastal segments present a V_{R} ranging between 8 and 10 (Fig. 4b). However, the blue colours, indicating a low vulnerability index, predominate in the ranking estimated using V_{I}, V_{M} and V_{ESI}

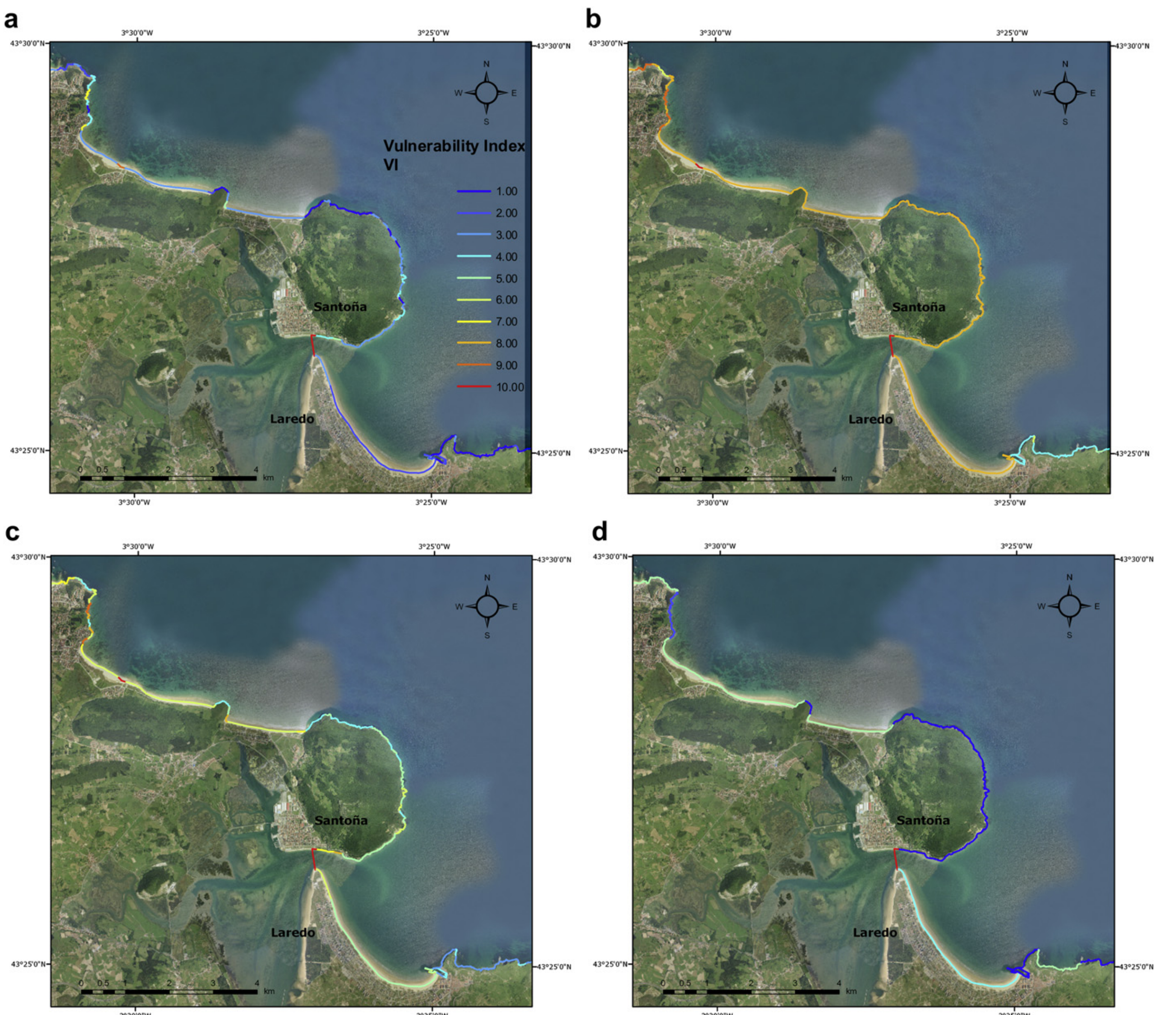

Fig. 4. Oil spill vulnerability indexes for the Santoña Estuary area (see location in Fig. 1b): (a) V_{I} (integrated vulnerability index); (b) V_{R} (worst-case vulnerability index); (c) V_{M} (average vulnerability index); (d) V_{ESI} (ESI-based index).

Table 5
Example of cross-tabulation matrix. p_{ii} are the proportions of observed agreements between the two methods (in this example V_I and V_R) for each category.

	Categories	V_I				
		1	2	…	10	Total
V_R	1	p_{11}	p_{12}		p_{110}	$p_{1.}$
	2	p_{21}	p_{22}		p_{210}	$p_{2.}$
	3					
	…					
	10				$p11$	$p10.$
	Total	$p_{.1}$	$p_{.2}$		$p_{.10}$	1

(Fig. 4a, c and d). The same behaviour is found for the rest of the coast.

In order to obtain a quantitative assessment of what was explored in Fig. 4, the kappa coefficient of agreement has been applied to the entire coast. As mentioned before, the V_I index was the control method which has been compared with the others classifications.

To measure agreement between the rankings obtained by applying V_I and those calculated using V_R, V_M and V_{ESI}, three cross-tabulation matrixes were constructed (V_I–V_R, V_I–V_M and V_I–V_{ESI}) (see example in Table 5).

Calculating the weighted kappa coefficient, κ_w (Eqs. (12) and (14)) for our data (ten categories and 1237 cases or coastal segments), the value of κ_w for the V_I–V_R comparison was 0.55; for V_I–V_M was 0.8 and for V_I–V_{ESI} was 0.77.

Monserud and Leemans (1992) proposed a ranking for the degree of agreement depending on the kappa value: (<0.05: no agreement; 0.05–0.20: very poor; 0.21–0.40: poor; 0.41–0.55: fair; 0.56–0.70: good; 0.71–0.85: very good; 0.86–0.99: excellent; 1: Perfect). Following this classification, the degree of agreement between the integrated vulnerability index, V_I, and the worst-case index, V_R, was fair, while both the comparisons V_I–V_M and V_I–V_{ESI}, gave an agreement classified as very good.

The differences between the classifications can also be examined in Fig. 5, which shows the empirical pdfs corresponding to the vulnerability data calculated using each one of the four methods. The pdfs show that the integrated index, V_I, groups most of the assessment units (80%) into the lowest vulnerability scores (1 and 2). The ESI-based index, V_{ESI}, also presents a high percent (50%) of the coastal segments within the 1 and 2 values. However, this classification gives the peak of probability (32%) to vulnerability 5, located in the mean position of the ranking, and presents the highest percentage of coastal segments with a score of 10 (7%). The pdf corresponding to the mean index, V_M, is the most uniform, presenting the lowest probability for the extreme vulnerability values (1, 9 and 10). The worst-case index, V_R, displays a bimodal behaviour with two peaks of probability for 8 and 4 with 50% and 26% of the assessment units, respectively.

The comparison of these pdfs with those presented in Fig. 2, shows a strong influence of the physical index, I_P, on the classification given by V_I. This was expected given the expression used to calculate the integrated index (Eq. (15)). Moreover, it seems that V_R has a close relation with the I_B and I_E indexes. The later can be checked in Fig. 6, which represents the percentage of coastal segments whose 'worst index' was the I_P, I_B or I_E index. Note that, as the observation of the V_R empirical pdf indicated, the 'worst index' in 90% of the coastal segments was either the biological (59%) or the socio-economic index (26%) or both of them (5%). The physical index was only determinant in 10% of the segments (in 4% of whom the worst index was also the I_E) and in less than 1% of the assessment units the three indexes simultaneously had the highest score.

The results of this comparative study are influenced by the characteristics (morphology, homogeneity, etc) of a specific coast. In the Cantabrian case, with a high percentage of segments included in the rocky shore type (steep coast predominantly exposed to the wave energy), the use of the V_R index leads to a conservative ranking, with a poor discrimination that is not very helpful in the coastal management. The kappa analysis gave quite a good agreement between the rest of the vulnerability index, V_I,

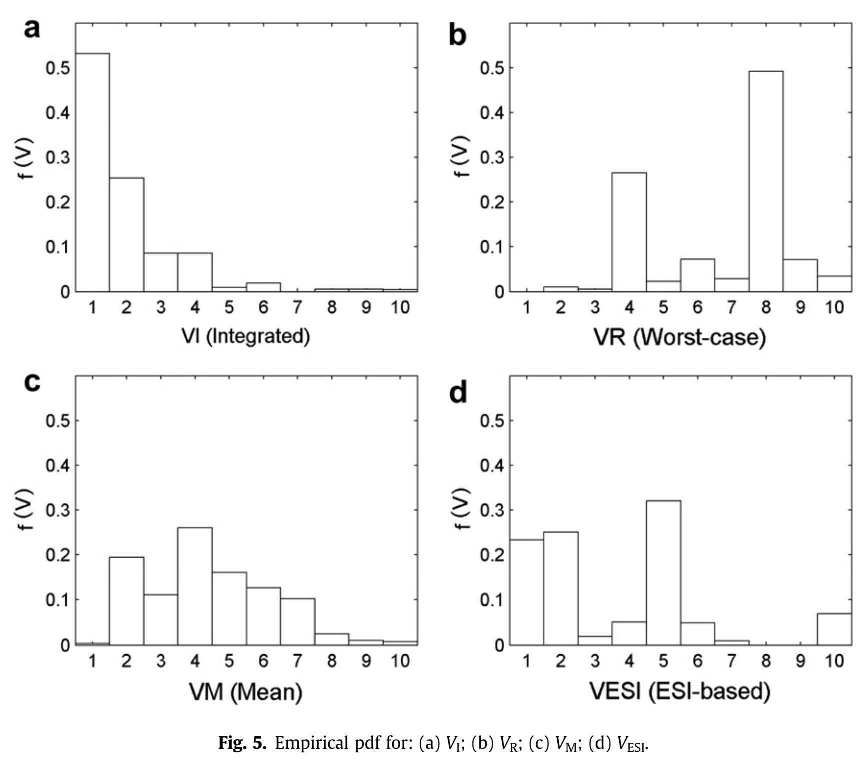

Fig. 5. Empirical pdf for: (a) V_I; (b) V_R; (c) V_M; (d) V_{ESI}.

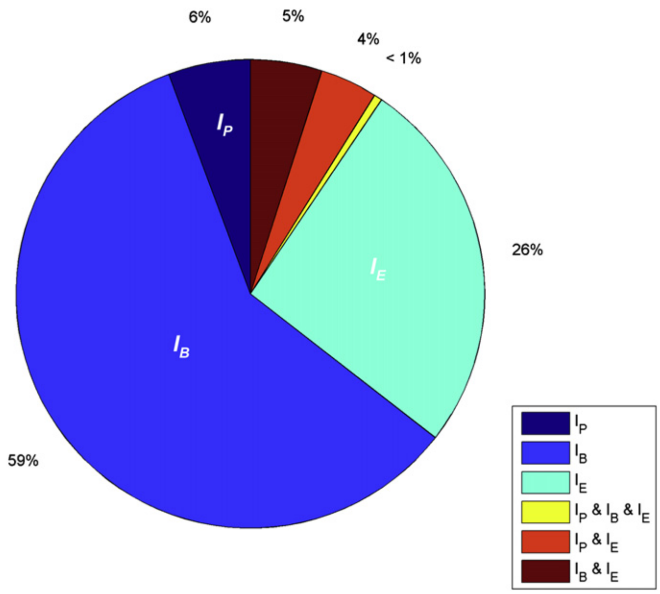

Fig. 6. Percent of each intermediate index in the V_R index.

V_M and V_{ESI}, although it must be emphasized the flexibility that the V_I and V_M procedures provide by allowing three indexes for each coastal segment: I_P, I_B and I_E.

The socio-economic aspects, I_E, are not usually included in a vulnerability assessment. However, from a practical point of view, this is one of the key elements which determine the location of mechanical protection measures such as oil spill containment booms, trying to protect people and their activities from contamination. Although, as mentioned before, most of the works related to oil spill vulnerability include only physical and biological characteristics, during the application of this methodology to the Cantabrian coast, it was found that, surprisingly, the most costly index to obtain was the biological index, I_B. While the calculation of I_B required extensive field works, most of the socio-economic data were obtained from official publications.

Finally, the V_I based on the analysis of the results of a representative survey, is proposed as the best method of integration, as it boosts the public participation that is one of the main phases in the implementation of Integrated Coastal Zone Management (IZCM).

4. Conclusions

This study has developed a methodology to assess the oil spill vulnerability of a coast based on its physical (physical index, I_P), biological (biological index, I_B) and socio-economic (socio-economic index, I_E) characteristics. The research work has focused on integrating all these aspects in one single index with the aim of providing a rational basis to assign priority protection to different coastal areas.

The results of the application of the methodology to the Cantabrian coast (ten categories and 1237 cases or coastal segments) indicate that almost 40% of the coastal segments present an I_P of 1, and 65% have an I_P of less than 4. This is due to the study coast being predominantly exposed to the wave energy and steep (see Table 2). Regarding the biological aspects, most of the Cantabrian environments present a conservation state between moderate and good or high (80% of the assessment units has a conservation index of 3 (see Table 3)) having a high resilience or capacity of recovering from an oil spill.

The socio-economic analysis clearly shows that this coast is mainly divided into two groups, one with a very low I_E (50% of the coastal segments), corresponding to rocky shore type environments, and another with a high I_E (34%), the areas surrounding the estuaries, which usually concentrate all the economic activities (fishery, shellfish, tourism, harbour activity and recreation).

To obtain one vulnerability index that represents all these characteristics, three methods have been proposed: the worst-case vulnerability of a segment, V_R; the average vulnerability of a segment, V_M and the integrated vulnerability index, V_I. The later is calculated by means of a Delphi survey, taking into account the participation of different stakeholders belonging to the most relevant socio-economic sectors related to the Cantabrian coast.

With the purpose of obtaining some helpful conclusions and providing a useful decision support tool, the coastal categorization resulting from the application of these approaches, as well as the vulnerability scores assigned by the modified version of the ESI proposed by Juanes et al. (2007) for this coastal area, V_{ESI}, have been analyzed.

The weighted kappa coefficient of agreement, κ_w, has been derived taking the survey-based index, V_I, as the control method. The value of κ_w for the V_I–V_R comparison was 0.55 (fair); for V_I–V_M was 0.8 (very good) and for V_I–V_{ESI} was 0.77 (very good).

Further analysis using the empirical histograms of the data, shows that V_I depends, quite closely, on the physical ranking established by I_P and groups most of the assessment units (80%) into the lowest vulnerability scores (1 and 2). The ESI-based index, V_{ESI}, also presents a high percent (50%) of the coastal segments within the 1 and 2 values. However, this classification gives the peak of probability (32%) to the vulnerability 5, located in the mean position of the ranking, and it presents the highest percent (7%) of coastal segments with the maximum vulnerability score (10). The histogram corresponding to the mean index, V_M, is the more uniform one, presenting the lowest probability for the extreme vulnerability values (1, 9 and 10). The worst-case index, V_R, displays a close relation with the I_B and I_E indexes. In 90% of the coastal segments, the worst index was either the biological (59%) or the socio-economic index (26%) or both of them (5%).

Some conclusions have been obtained from the application of these integration methods to the Cantabrian coast. The V_R index leads to a much too conservative ranking, not very helpful in the coastal management. If the coast is mainly homogeneous, the rest of the methods, V_I, V_M and V_{ESI}, give comparable classifications. However, V_M and V_I, based on three intermediate indexes and including socio-economic aspects, give more flexibility allowing three indexes for each coastal segment. The inclusion of the socio-economic index does not involve much extra-effort while providing relevant information if the study coast has areas with high population density and significant tourism or industrial activities.

Finally, the V_I procedure is proposed as the more advisable. As well as the V_M index, it provides three indexes for each coastal segment but, in addition, using this index promotes the public participation that is a key element in the implementation of Integrated Coastal Zone Management (IZCM).

Acknowledgements

This work has been partly funded by the Spanish Ministry of Education and Science under the research project TRA2007-65133/TMAR (PREVER project) and by the Marcelino Botin Fundation. S. Castanedo would like to thank the Spanish Ministry of Science and Technology for the support under Ramon and Cajal Program.

References

Adler, E., Inbar, M., 2007. Shoreline sensitivity to oil spills, the Mediterranean coast of Israel: assessment and analysis. Ocean & Coastal Management 50, 24–34.
Brown Jr. G. (1992) Replacement cost of birds and mammals. Available at: http://www.evostc.state.ak.us/Publications/economic.cfm. Last accessed: February 2007.
Castanedo, S., Medina, R., Losada, I.J., Vidal, C., Mendez, F.J., Osorio, A., Juanes, J.A., Puente, A., 2006. The Prestige oil spill in Cantabria (Bay of Biscay). Part I: operational forecasting system for quick response, risk assessment and protection of natural resources. Journal of Coastal Research 22 (6), 1474–1489.
Castanedo, S., Pombo, C., Fernandez, F., Medina R., Puente, A., and Juanes, J.A., (2008) Oil Spill Vulnerability Atlas for the Cantabrian Coast (Bay of Biscay, Spain). In: Proc. 20th International Oil Spill Conference. Savannah, Georgia, pp. 137–144.
Cohen, J., 1960. A coefficient of agreement for nominal scales. Educational and Psychological Measurement 20, 37–46.
Cohen, M.J., 1995. Technological disasters and natural resource damage assessment: an evaluation of the Exxon Valdez oil spill. Land Economics 71 (1), 65–82.
Deloitte, Exceltur, 2005. Impactos sobre el entorno, la economía y el empleo de los distintos modelos de desarrollo turístico del litoral Mediterráneo español, Baleares y Canarias. Anexo Metodológico, Madrid (In Spanish).
Dunford, R.W., Ginn, T.C., Desvousges, W.H., 2004. The use of habitat equivalency analysis in natural resource damage assessments. Ecological Economics 48, 49–70.
Fleiss, J.L., Cohen, J., 1973. The equivalence of weighted kappa and the intraclass correlation coefficient as a measure of reliability. Educational and Psychological Measurement 33, 613–619.
FLTQ (Fundación Leonardo Torres Quevedo) (2006) Programa de predicción, protección y evaluación del vertido del buque Prestige en las costas de Cantabria. (In Spanish).
French, D., 2004. Oil spill impact modeling: development and validation. Environmental Toxicology and Chemistry 23 (10), 2441–2456.
Garcia Negro, M.C., Villasante, C.S., Carballo Penela, A., 2007. Compensating system for damages caused by oil spill pollution: background for the Prestige assessment damage in Galicia, Spain. Ocean & Coastal Management 50, 57–66.
Garza-Gil, M.D., Suris-Regueiro, J.C., Varela-Lafuente, M.M., 2006. Assessment of economic damages from the Prestige oil spill. Marine Policy 30, 544–551.
Gelin, A., Gravez, V., Edgar, G.J., 2003. Assessment of Jessica oil spill impacts on intertidal invertebrate communities. Marine Pollution Bulletin 46, 1377–1384.
Gomez Gesteira, J.L., Dauvin, J.C., Salvande, M., 2003. Taxonomic level for assessing oil spill effects on soft-bottom sublittoral benthic communities. Marine Pollution Bulletin 46, 562–572.
Gundlach, E.R., Hayes, M.O., 1978. Vulnerability of coastal environments to oil spill impacts. Marine Technology Society Journal 12, 18–27.
Guven, K.G., Okus, E., Unlu, S., Dogan, E., Yuksek, A., 1998. Oil pollution of marine organisms after Nassia tanker accident in the Black Sea, Bosphorus and the Sea of Marmara. Turkish Journal of Marine Sciences 4 (1), 3–10.
Hanna, R.G.M., 1995. An approach to evaluate the application of the vulnerability index for oil spills in tropical red sea environments. Spill Science and Technology Bulletin 2, 171–186.
Hayes, M.O., Hoff, R., Michel, J., Scholz, D., Shigenaka, G., 1992. An Introduction to Coastal Habitats and Biological Resources for Oil Spill Response. National Oceanic and Atmospheric Administration, Seattle, Washington. Report No. HAZMAT 92-4.
Holman, R., 1986. Extreme value statistics for wave run-up on a natural beach. Coastal Engineering 9, 527–544.
Juanes, J.A., Puente, A., Revilla, J.A., Alvarez, C., Medina, R., Castanedo, S., Morante, L., Gonzalez, S., Garcia-Castrillo, G., 2007. The Prestige oil spill in Cantabria (Bay of Biscay). Part II: environmental assessment and monitoring of coastal ecosystems. Journal of Costal Research 23 (4), 978–992.
Loureiro, M.L., Ribas, A., Lopez, E., Ojea, E., 2006. Estimated cost and admissible claims linked to the Prestige oil spill. Ecological Economics 59, 48–63.
Michel, J., Hayes, M.O., Brown, P.J., 1978. Application of an oil spill vulnerability index to the shoreline of lower cook inlet, Alaska. Environmental Geology 2, 107–117.
Monserud, R.A., Leemans, R., 1992. Comparing global vegetation maps with the Kappa statistic. Ecological Modelling 62, 275–293.
Nansingh, P., Jurawan, S., 1999. Environmental sensitivity of a tropical coastline (Trinidad, West Indies) to oil spills. Spill Science & Technology Bulletin 5 (2), 161–172.
OJEC (Official Journal of European Communities) (2002). Recommendation of the European Parliament and of the Council of 30 May 2002 concerning the implementation on Integrated Coastal Zone Management in Europe. (2002/413/EC).
O'Sullivan A.J., Jacques, T.G. (2001). Impact Reference System. Effects of Oil in the Marine Environment: Impact of Hydrocarbons on Fauna and Flora. European Commission. Directorate General Environment. Bélgica. Internet edition.
Petersen, J., Michel, J., Zengel, S., White, M., Lord, C. Park, C. (2002) Environmental Sensitivity Index Guidelines. Version 3.0. NOAA Technical Memorandum NOS OR & R 11. Seatle: Office of Response and Restoration, National Oceanic and Atmospheric Administration.
Peterson, C.H., 2000. The Exxon Valdez oil spill in Alaska: acute, indirect and chronic effects on the ecosystem. Advances in Marine Biology 39, 3–84.
Preston, Thorgrimson, Shildler, Gates and Ellis (1990) An assessment of the impact of the Exxon Valdez oil spill on the Alaska tourism industry. McDowell Group. Available at: http://www.evostc.state.ak.us/Publications/economic.cfm. Last accessed: February 2007.
Roach, B., Wade, W.W., 2006. Policy evaluation of natural resources injuries using habitat equivalency analysis. Ecological Economics 58, 421–433.
Ratsimandresy, A.W., Sotillo, M.G., Carretero Albiach, J.C., Álvarez Fanjul, E., Hajji, H.A., 2008. 44-year high-resolution ocean and atmospheric hindcast for the Mediterranean Basin developed within the HIPOCAS Project. Coastal Engineering 55 (11), 827–842.
Sloan, N.A. (1999). Oil Impacts on Cold-Water Marine Resources: A Review Relevant to Parks Canada's Evolving Marine Mandate. Parks Canada. National Parks, Occasional Paper no. 11. Queen Charlotte, BC, 67 p.
Tsouk, E., Amir, S., Goldsmith, V., 1985. Natural self-cleaning of oil-polluted beaches by waves. Marine Pollution Bulletin 16 (1), 11–19.
Van der Meer, J.W., 1993. Conceptual design of rubble mound breakwaters. Delft Hydraulics 483.
Wieczorek, A., Dias-Brito, D., Carvalho Milanelli, J.C., 2007. Mapping oil spill environmental sensitivity in Cardoso Island Park and surroundings areas, Sao Paulo, Brazil. Ocean & Coastal Management 50, 872–886.
Wirtz, K.W., Liu, X., 2006. Integrating economy, ecology and uncertainty in an oil-spill DSS: the Prestige accident in Spain, 2002. Estuarine, Coastal and Shelf Science 70, 525–532.
Zenetos, A., Hatzianestis, J., Lantzouni, M., Simboura, M., Sklivagou, E., Arvanitakis, G., 2004. The Eurobulker oil spill: mid-term changes of some ecosystem indicators. Marine Pollution Bulletin 48, 122–131.