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Assessing anthropogenic pressures on estuarine fish nurseries along the Portuguese coast: A multi-metric index and conceptual approach

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Abstract

Estuaries are among the most productive ecosystems and simultaneously among the most threatened by conflicting human activities which damage their ecological functions, namely their nursery role for many fish species. A thorough assessment of the anthropogenic pressures in Portuguese estuarine systems (Douro, Ria de Aveiro, Mondego, Tejo, Sado, Mira, Ria Formosa and Guadiana) was made applying an aggregating multi-metric index, which quantitatively evaluates influences from key components: dams, population and industry, port activities and resource exploitation. Estuaries were ranked from most (Tejo) to least pressured (Mira), and the most influential types of pressure identified. In most estuaries overall pressure was generated by a dominant group of pressure components, with several systems being afflicted by similar problematic sources. An evaluation of the influence of anthropogenic pressures on the most important sparidae, soleidae, pleuronectidae, moronidae and clupeidae species that use these estuaries as nurseries was also performed. To consolidate information and promote management an ecological conceptual model was built to identify potential problems for the nursery function played by these estuaries, identifying pressure agents, ecological impacts and endpoints for the anthropogenic sources quantified in the assessment. This will be important baseline information to safeguard these vital areas, articulating information and forecasting the potential efficacy of future management options.

Keywords: Estuaries; Anthropogenic pressures; Fish nursery; Multi-metric index; Conceptual model; Portugal

1. Introduction

Coastal transition ecosystems, such as estuaries and coastal lagoons, are amongst the most productive and valuable aquatic ecosystems on Earth (Costanza et al., 1997) and are recognized worldwide as an important component of continental coasts in terms of their biological importance and utilization by humans (Cooper et al., 1994; Marques et al., 2004).

Many authors have emphasized the importance of estuarine areas and their associated coastal waters, as nursery for fish, and their role in supporting the offshore stocks of economically valuable species (Marchand, 1980; Costa and Bruxelas, 1989; Blaber et al., 2000; Beck et al., 2001; Gillanders et al., 2003; Able, 2005). These systems are particularly used by juveniles of many fish species because of the potential advantages they

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provide for the growth and survival of young fish, namely high prey availability, refuge from predators and good environmental conditions (Haedrich, 1983; Miller et al., 1985; Lenanton and Potter, 1987; Beck et al., 2001).

In general, estuaries host special habitats of great ecological value and of particular importance as nursery and feeding areas for young fish namely saltmarsh, oyster and seagrass beds (Labourg et al., 1985; Weinstein and Brooks, 1983; Cattrijsse et al., 1994; Costa et al., 1994; Jackson et al., 2001; Beck et al., 2001).

In contrast with their ecological importance, estuaries are amongst the most modified and threatened aquatic environments (Blaber et al., 2000). Rapid population growth and uncontrolled development in many coastal regions worldwide have intensified the multi-specific interests and activities which develop in and around estuaries. Consequently estuaries exhibit a wide array of human impacts that collide with their ecological function threatening the long term viability and health of these important ecotones (Goldberg, 1995; Costa et al., 2002a; Kennish, 2002).

Although scientists and engineers have long recognized that human activities can significantly alter the nature of the marine environment, negatively affecting public health and the well-being of marine organisms (Goldberg, 1995), historically fisheries managers have considered fisheries as the most threatening anthropogenic factor concerning fish populations (Boreman, 1997; Johnson et al., 1998). In recent years there has been an increasing concern about the role that other anthropogenic factors might play in the decline of commercially and recreationally important marine fish species (Grosse et al., 1997). Agricultural, industrial and engineering projects can alter the shape and nature of the estuaries. Domestic and industrial discharges along with other pollution sources and heavy fishing pressure have a significant effect on abundance and structure of estuarine communities (Haedrich, 1983). Recent studies are now considering habitat loss as a greater problem than pollution itself (Cattrijsse et al., 2002; Kennish, 2002).

Scientists can aid in the environmental management of these conflicts by providing high-quality technical information to decision-makers, yet in scientifically valid forms. In recent years this challenge has been met through the use of multi-metric index approaches, that have been developed for simplifying the use of extensive ecological data (Cooper et al., 1994; Boesch, 2000; Ferreira, 2000; Paul, 2003), and with the development of indicators as management tools to address environmental issues (Belfiore, 2003; Aubry and Elliott, 2006).

The implementation of the European Water Framework Directive (WFD; 2000/60/EC) establishes the guidelines for water resources management with well defined objectives for the protection of groundwater, inland, estuarine and coastal waters. This framework requires Member States to assess the Ecological Quality Status of transitional and coastal waters by 2006 and achieve at least good ecological status in all water bodies by 2015. The WFD outlines that Member States must collect information on the type and magnitude of significant anthropogenic pressures, and identify in specific cases Heavily Modified Water Bodies.

Estuaries along the Portuguese coast play an acknowledged role as nursery areas for several commercially important fish species, although their importance has not yet been comprehensively assessed (Cabral and Costa, 2001; Erzini et al., 2002; Martinho, 2005; Cabral et al., in press). Some have been studied for several years (Costa and Cabral, 1999) while others have seldom been studied even in terms of their fish assemblages. Simultaneously, these systems are intensely exploited and impacted by human activities (Bettencourt and Ramos, 2003). Moreover there has been little or no application of the fragmented scientific assessments made in terms of stimulating local or national planning and management systems. It is therefore necessary to create baseline studies and collect data from multiple sources that will allow the establishment of a strong scientific background in order to promote management plans and fulfil the WFD requirements. Several methodologies for an accurate and consistent evaluation are being developed (see Rogers and Greenaway, 2005; Aubry and Elliott, 2006) namely for assessing anthropogenic pressures and determining the origin of ecological degradation (see Borja et al., 2006; Ferreira et al., 2006). Identifying sources and recognizing respective effects allows the classification of which are potentially most damaging, predict effects, consequences and plan mitigation measures.

In the present paper, anthropogenic pressures on eight estuarine systems of the Portuguese coast (Douro, Ria de Aveiro, Mondego, Tejo, Sado, Mira, Ria Formosa and Guadiana) are thoroughly assessed using a multi-metric index, in order to: rank and compare the main pressures, identify the estuaries that may represent the most vulnerable cases and evaluate possible effects on the fish species which depend on them for nursery areas. The vulnerability of these estuaries will be assessed together with the pressures as a measure of the estuaries natural response and buffering capacity to human activities. In order to articulate these findings and to easily transpose this information to non-scientific managers and politicians an ecological conceptual model will be developed regarding the expected impacts on the estuarine systems generated by the identified anthropogenic pressures.

This approach is most valuable since it promotes a better understanding of the linkages between the components of the environment, allows the prediction of the outcome of natural and anthropogenic pressures and provides a basis, as well as stipulating targets, for future research (Peterson, 2003). As it is not possible to constrain all human activities on estuaries, or even monitor all effects, defining main sources and their consequent ecological endpoints can be an effective management tool.

This study should prove to be a valuable baseline and priority defining tool in the development of management plans for these estuaries, contributing to the safeguard of nursery areas and of estuarine-dependent marine fish stocks.

2. Materials and methods

The anthropogenic pressures occurring in eight estuarine systems of the Portuguese coast (Douro, Ria de Aveiro, Mondego, Tejo, Sado, Mira, Ria Formosa and Guadiana) were assessed through the determination of a multi-metric index which assembles a large volume of information. This set of estuaries (Fig. 1) was selected for both their size and ecological importance, and for the availability of data necessary for this approach.

Each estuarine system was characterized by means of a natural vulnerability descriptor and 12 anthropogenic pressure descriptors, each descriptor being quantified by the merging of several metrics (Table 1).

Natural vulnerability consists of a measure of the natural aptitude of an estuary to respond to pressures especially in terms of water quality and consequently of its buffering capacity (adapted from Ferreira, 2000). Table 1 lists the natural vulnerability and pressure descriptors, as well as the corresponding metrics used to calculate each descriptor and respective data sources. The most important criteria in the selection of descriptors and metrics were suitability to these estuaries and also data reliability and availability. Data was acquired mainly from several governmental and public sources and merged to obtain a database for the eight studied estuarine systems referring to the period between 2000 and 2005. Government agency and public institution records constitute consistent sources of data on various subjects, particularly on those required for the present approach.

The index approach was adapted from Kranjc and Glavič (2005), who designed a composite sustainable development index in order to enable a comparison of companies based on a large number of performance measures.

Each of the pressure metrics (P) (Table 1) is initially classified either as a pressure contributing metric (P^+), whose increasing value represents a pressure on the estuary or as a pressure relieving metric (P^-) whose increasing value contributes to the decrease of pressure. Most metrics are pressure contributing, for example untreated sewage discharges, but some are considered pressure relieving metrics, such as number of waste water treatment plants.

To solve the problem of different measurement units of the metrics and achieve compatibility of all data, each metric value is normalized (values ranging from 0 to 1) using one of the following equations (for P^+ or P^-):

$$P^+_{\mathrm{N},ij} = \frac{P^+_{\mathrm{A},ij} - P^+_{\mathrm{min},j}}{P^+_{\mathrm{max},j} - P^+_{\mathrm{min},j}} \quad ; \quad P^-_{\mathrm{N},ij} = 1 - \frac{P^-_{\mathrm{A},ij} - P^-_{\mathrm{min},j}}{P^-_{\mathrm{max},j} - P^-_{\mathrm{min},j}} \tag{1}$$

where P_N represents the normalized pressure value and P_A the original pressure value, for an estuary i of the full set of estuaries j.

Fig. 1. Map of Portugal with the location of the eight estuaries: Douro, Ria de Aveiro, Mondego, Tejo, Sado, Mira, Ria Formosa and Guadiana.

Table 1
Anthropogenic pressure components, descriptors and metrics and data sources used in the determination of the multi-metric index

Component	Descriptor	Metric	Data source
Natural vulnerability	Natural vulnerability	Estuarine area; intertidal area; percentage of intertidal area; mean depth; mean river flow; mean residence time; volume; tidal range.	'Instituto Nacional da Água' — National Water Institute (INAG); Bettencourt and Ramos (2003).
Population and industry	Population	Watershed inhabitant number; estuarine surrounding area inhabitant number and density.	'Instituto Nacional de Estatistica' — National Statistics Institute (INE); INAG.
	Industry	Number of agriculture and fishing industries; number of transforming industries.	INE.
	Industrial loads	Industrial loads volume; biological oxygen demand, chemical oxygen demand and total suspended solids of generated and affluent industrial loads.	INE.
	Water and sediment quality	Quality of watershed surface water for multiple uses (criteria based on heavy metals, nutrients, fecal coliforms, total suspended solids, oxygen demands, pH and conductivity); sediment contamination in the estuary, according to Long et al. (1995); nitrogen and phosphorus loads into the estuary per year.	INAG; Bettencourt and Ramos (2003).
	Wastewater treatment	Number of waste water treatment plants; percentage of watershed resident population not served by sewage network; percentage of watershed resident population served by sewage with treatment; percentage of watershed direct pollution sources constituted by direct discharges.	INAG; 'Inventário Nacional de Sistemas de Abastecimento de Água e de Águas Residuais' — Water Supply and Wastewater National Inventory (INSAAR — INAG); Bettencourt and Ramos (2003).
Port activities	Dredging	Number of estuarine dredged areas per year; volume of dredged material in the estuary per year.	INAG; Local Port Authorities.
	Port activities	Number of commercial ports; annual ship traffic; number of licensed boats per estuarine ports.	'Associação dos Portos' — National Ports Association.
Dams	Dams	Number of large dams ($>10^5$ m^3 or >15 m high) in watershed; distance from mouth of the estuary to first dam.	INAG and 'Comissão Nacional das Grandes Barragens' — Large Dams National Comission.
Resource exploitation	Bank regulation	% of regulated estuarine bank length.	Determined from military maps and aerial photographs.
	Agriculture	Agricultural surface area; used agricultural surface area and its percentage in total agricultural surface area.	INE.
	Fishing	Number of licensed fishing boats per estuarine ports	'Direcção Geral das Pescas e Aquicultura' — National Directorate for Fisheries and Aquaculture (DGPA).
	Aquaculture	Number of fish farms; area of fish and shellfish farms in the estuary and percentage in total estuarine area occupation; sanitary classification.	'Instituto de Investigação das Pescas e do Mar' — National Fisheries Institute (IPIMAR).

For the natural vulnerability descriptor, 0 represents the least vulnerable of the systems and 1 the most vulnerable, while for the anthropogenic pressure descriptors 0 represents the lowest pressure and 1 the highest pressure on the considered set of estuaries. In this manner, all variables are assigned rating values based on comparable scales (Cooper et al., 1994).

After normalizing all metrics for each descriptor, they are combined into an aggregate index simply by averaging the scores of all metrics available for each descriptor. Averaging was used rather than the alternative technique of summing the scores because the number of available metrics varied among the descriptors. As in Borja et al. (2006) pressure metrics were not attributed different relative weights.

The 12 pressure descriptors of the estuarine systems were comparatively analysed using a Principal Components Analysis (PCA), after running a Detrended

Component Analysis (DCA) using Canoco (ter Braak, 1995). The PCA aimed to outline the similarities among estuarine systems in terms of the pressures that affect them and patterns in the intensity of these pressure descriptors.

Pressures of similar origin appeared associated among themselves in the PCA diagram enabling the formation of four distinct groups of pressures. Given that the groups consisted of closely related pressures it was decided to use these groups for further analysis as a form of simplifying the results. Four groups of pressure descriptors (referred as components) were established. Each estuary is now described by the values of each of these four components, which consist of the average of the descriptors for each component. With this data a new PCA was run.

These estuaries are recognized as nursery areas for some commercially important fish species: common sole *Solea solea* (Linnaeus, 1758), senegalese sole *Solea senegalensis* Kaup, 1858, flounder *Platichthys flesus* (Linnaeus, 1758), sea bass *Dicentrarchus labrax* (Linnaeus, 1758), seabreams *Diplodus vulgaris* (Geoffroy Saint-Hilaire, 1817), *Diplodus sargus* (Linnaeus, 1758), *Diplodus annularis* (Linnaeus, 1758), *Diplodus bellottii* (Steindachner, 1882) and pilchard *Sardina pilchardus* (Walbaum, 1792).The importance of each of these species within the eight estuaries was categorized based on data for presence, mean and maximum densities of juveniles in the considered time period (Cabral, unpublished data; Cabral and Costa, 2001; Costa et al., 2002b; Bexiga, 2002; Erzini et al., 2002; Costa, 2004, 2005; Martinho, 2005; Pombo et al., 2005; Vinagre et al., 2005; Cabral et al., in press). The importance of each species was summarized by a relative importance score of 0, 1, 2 or 3.

In order to determine which species would be most related to the different groups of pressures a Correspondence Analysis (CA) was performed with the data of the anthropogenic pressures of each estuary used as a co-variable data matrix. This analysis was performed using Canoco (ter Braak, 1995) and should reveal if any species are affected by particular pressures.

An ecological conceptual model was built, based on other models by Harwell et al. (1999), Gentile et al. (2001), Peterson (2003) and Serveiss et al. (2004) using peer reviewed data and existing information on the connections between pressures and their impacts in ecosystems and communities. In this way linkages are defined between: the sources of anthropogenic pressures found in this set of estuaries; the specific pressures through which they cause impacts on the ecosystem and the identified consequent endpoints relevant for their ecological importance, particularly as fish nursery areas for commercially important species.

3. Results

3.1. Natural vulnerability

Assessment of natural vulnerability of the estuaries entails a characterization of the hydrology and geomorphology of the systems (Table 2), as well as the representation of scores obtained by each estuarine system in radar type graphs (Fig. 2).

The considered features were found to differ greatly between all estuaries and each estuary acquires its high or low vulnerability from the counterbalance of its different features. The most striking differences are found between the larger estuaries (in area, mean depth and volume) such as the Tejo and Sado, which also have the highest mean residence times, and smaller systems such as the Mira and Douro. The extension and importance of intertidal areas (in % of total estuarine area) is a markedly distinguishing feature of the coastal lagoons Ria de Aveiro and Ria Formosa, which also have the lowest mean depths. An extremely high mean river flow distinguishes the Douro estuary from the remaining despite its small dimension.

The Tejo estuary stands out as the least vulnerable (score 0.32) and the Mira as the most sensitive of the systems (score 0.78). The Tejo is the largest of the systems, only weakened by a high residence time, whereas the Mira

Table 2
Hydrologic and geomorphologic characteristics used for Natural Vulnerability characterization of the estuarine systems

Estuary	Estuarine area (km^2)	Intertidal area (km^2)	Intertidal area (% of total area)	Mean depth (m)	Mean river flow ($m^3\ s^{-1}$)	Mean residence time (days)	Volume (m^3)	Tidal range (m)
Douro	10	1	11	4	450	2	58.8×10^6	3.8
Ria de Aveiro	74	64	87	2	40	17	84×10^6	3
Mondego	10	6	64	2	79	3	22×10^6	3
Tejo	320	128	40	5	300	25	1900×10^6	2.6
Sado	180	78	44	6	40	30	500×10^6	2.7
Mira	5	2	42	4	3	15	27×10^6	2.4
Ria Formosa	91	74	81	1	2	2	92×10^6	2
Guadiana	20	5	24	3	80	12	100×10^6	3.43

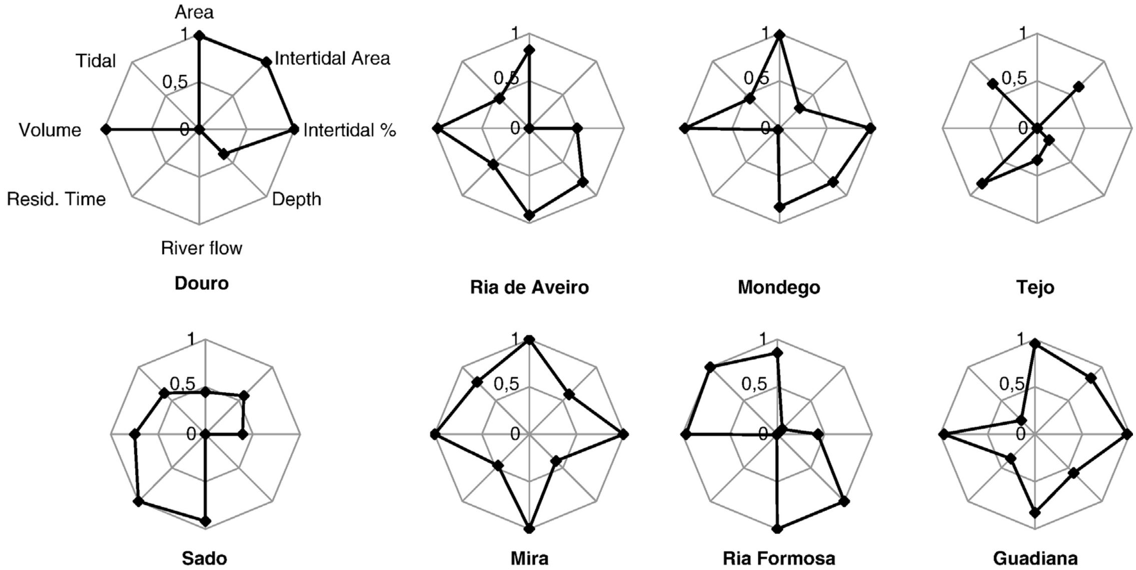

Fig. 2. Scores of Natural vulnerability descriptors for the eight estuaries. Scores range between 0 (low vulnerability) and 1 (high vulnerability).

is overall very vulnerable. Douro and Sado estuaries are quite robust to impacting pressures for opposing reasons, the first system is one of the smallest but has a strong flushing ability (due to high river flow and low residence time) and the second has large total area, intertidal areas and volume which give it characteristics close to those of the Tejo estuary. The coastal lagoons Ria de Aveiro and Ria Formosa are quite vulnerable systems, with very similar features already mentioned.

Natural vulnerability scores should always be taken into consideration as a counterbalancing measure when evaluating the remaining pressure vectors in each estuary, which means that low pressure levels on a weakly pressured estuary are not necessarily to be disregarded.

3.2. Anthropogenic pressures

After data collection concerning all metrics, normalization and determination of the scores for each of the 12 pressure descriptors, radar type graphs were built for each estuary (Fig. 3).

Most of the considered pressure metrics differ widely within the set of eight estuaries, consequently the types and intensities of anthropogenic pressure descriptors and components determined also differ.

The overall score (averaging all descriptors) shows: the Tejo estuary (overall 0.76) as the most pressured with high scores in almost all descriptors and, on the other end of the spectrum, the Mira estuary as the least pressured (overall 0.14). They represent the extremes of the national panorama. While the Tejo has very high, or even the highest, scores in all types of pressures, except for aquaculture and waste treatment, the Mira presents extremely low or zero values for all descriptors except for agriculture and waste treatment. The Sado and Douro estuaries are also highly pressured (scores 0.49 and 0.47 respectively), however, totally distinct types of pressures affect them. In fact in the Douro most of the pressures are due to high scores in descriptors of dams, population and industry associated pressures, and also port activities. On the other hand, the coastal lagoons show types of impacts similar to those of the Sado estuary, but with lower overall scores. The same applies to the Mondego estuary but with a lower overall score. These systems show high scores in agriculture, resource exploitation and port activities descriptors. The Guadiana estuary has quite a low pressure score, almost entirely due to its dam descriptor.

The Principal Component Analysis run with the 12 pressure descriptors (which accounted for 72.2 % of the total variance) allowed the identification of affinities between the estuaries in terms of pressures and revealed the colinearity of several of the descriptor vectors. This suggested that the groups of descriptors could be incorporated into new components in order to perform a new analysis, since the grouped descriptors were of similar activities, simplifying the assessment without losing information. The defined groups were: dams; population and industry — including population, waste treatment, industry, industrial loads, water and sediment quality descriptors; port activities — including dredging and port activities; resource exploitation — including

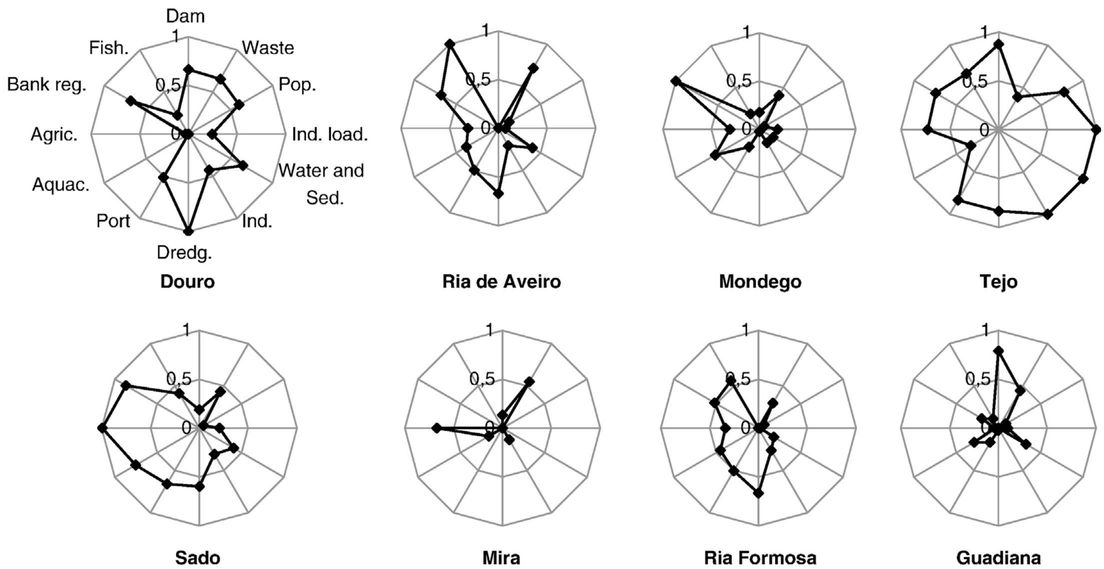

Fig. 3. Scores of Anthropogenic pressure descriptors for the eight estuaries. Scores range between 0 (low pressure) and 1 (high pressure). Vectors represent: Dams, Wastewater Treatment, Population, Industrial loads, Water and Sediment Quality, Industry, Dredging, Port activities, Aquaculture, Agriculture, Bank regulation and Fishing.

bank regulation, agriculture, aquaculture and fishing. In this manner, a new PCA was run based on new component pressure scores, determined by averaging the descriptor scores according to the new groups.

The new PCA analysis using the four pressure components accounted for 92.2 % of the total variance in the first two ordination axes and is represented in Fig. 4. The ordination diagram obtained reinforces the results revealed with the radar graphs. In fact, similarities in types of pressures of some estuaries which had been stressed in the radar graphs are confirmed in the ordination plot by the association of these estuaries and by their relationship with pressure component vectors.

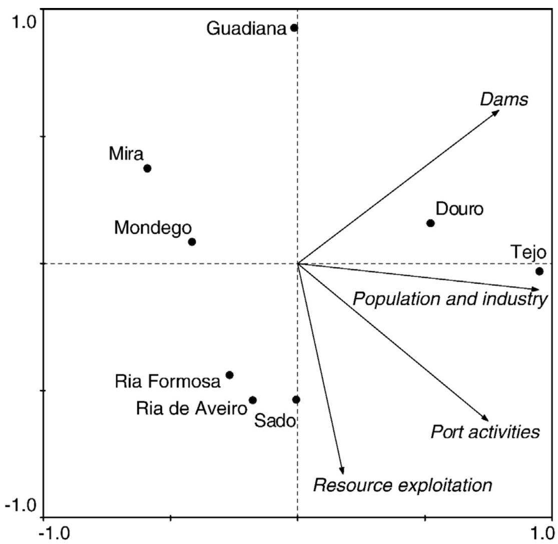

Fig. 4. Ordination plot of Principal Component Analysis for pressure components in the eight estuaries. Estuarine systems and vectors for anthropogenic pressures are represented.

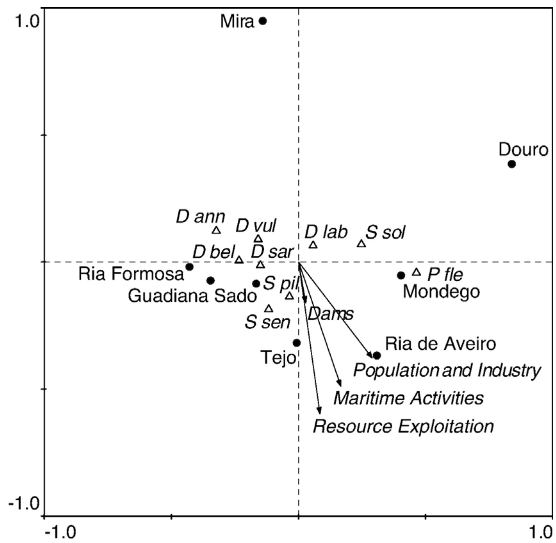

Fig. 5. Ordination plot of Correspondence Analysis for fish species that use the eight estuaries as nursery areas importance, with anthropogenic pressure components as co-variables. Estuarine systems, fish species and vectors for anthropogenic pressures are represented. *D lab* — *Dicentrarchus labrax*, *D ann* — *Diplodus annularis*, *D bel* — *Diplodus bellottii*, *D vul* — *Diplodus vulgaris*, *D sar* — *Diplodus sargus*, *P fle* — *Platichthys flesus*, *S pil* — *Sardina pilchardus*, *S sol* — *Solea solea*, *S sen* — *Solea senegalensis*.

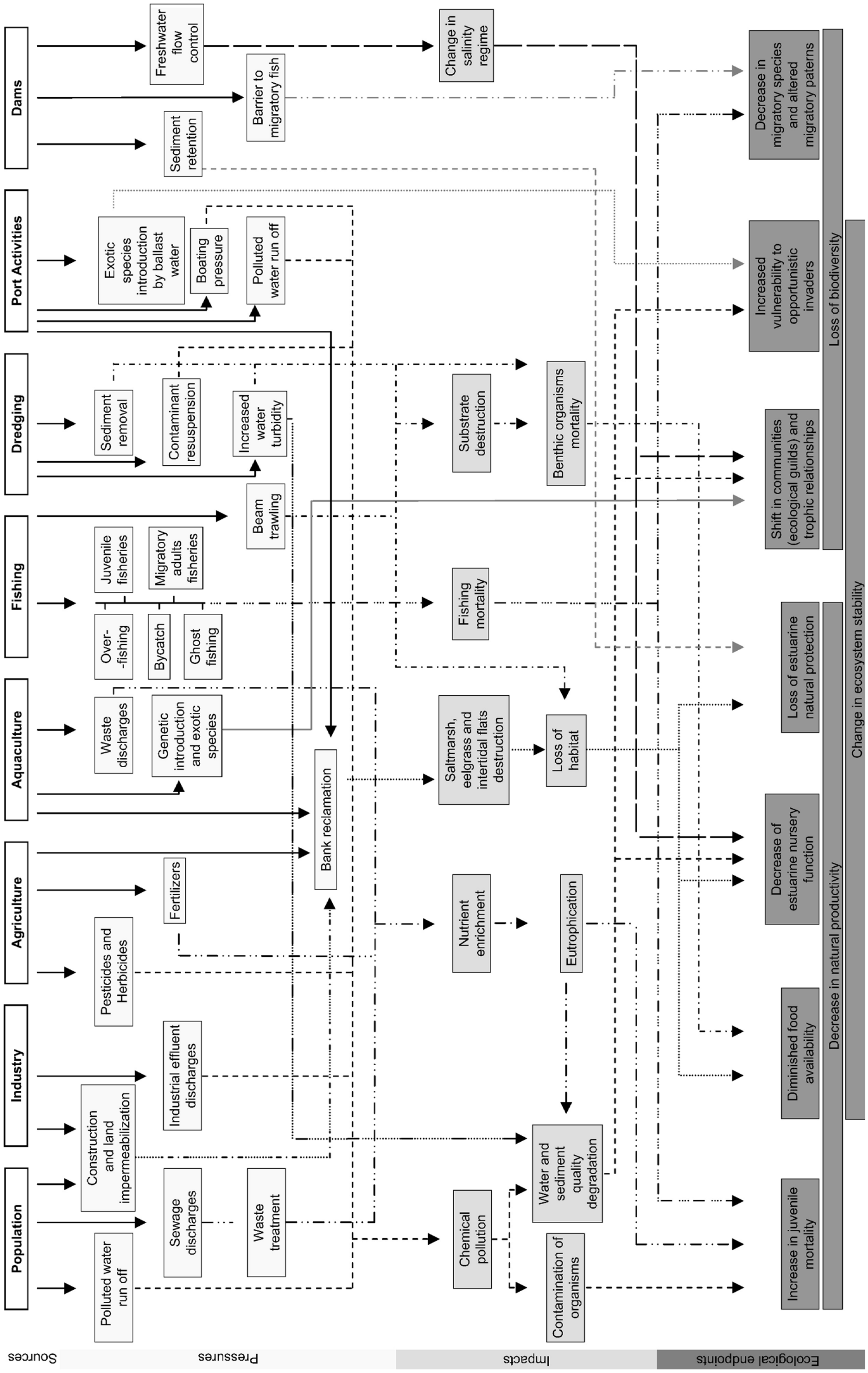

Fig. 6. Ecological Conceptual Model for Portuguese estuarine fish nurseries.

The Douro and Tejo estuaries are the most pressured. They are displaced due to the dams and population and industry component vectors in relation to the other estuaries. Ria de Aveiro, Sado and Ria Formosa form a group which is more associated with the resource exploitation component. Representation of the Guadiana estuary seems to be due to the dam component and lack of influence from the other vectors. Mira estuary is drawn opposing all pressure vectors and the Mondego seems to be dislocated towards the group with the coastal lagoons and the Sado estuary by the influence of the resource exploitation vector.

3.3. Anthropogenic pressures and nursery role for fish species

Correspondence analysis performed using fish species data and pressure data, as a supplementary covariable environmental data matrix, allowed the identification of the general pattern of importance of the species in the estuaries. This analysis accounted for 62.6 % of the total variance of the species–environment relation in the first two ordination axes (Fig. 5). A latitudinal gradient of estuaries (from South to North) is observed along the first axis. Species of seabreams of the genus *Diplodus* appear associated to the southern coast estuaries (Ria Formosa and Guadiana), while the flounder *P. flesus* is related with the northern estuaries (Douro, Ria de Aveiro and Mondego). Species as the common sole *S. solea*, senegalese sole *S. senegalensis*, sea bass *D. labrax* and pilchard *S. pilchardus* are common in most estuaries, and for that reason appear in the centre of the diagram.

Overlying the pressure vectors on the correspondence analysis between species and estuaries (which is done by using pressure data as a covariable data matrix), these appear very close and even overlapping, and do not define a pressure pattern on species distribution.

3.4. Ecological conceptual model

The ecological conceptual model built is presented in Fig. 6. From the multitude of anthropogenic pressure descriptors which were assessed and used in the index approach (Table 2) most were also incorporated in the model as pressure sources (Population, Industry, Agriculture, Fishing, Dredging, Port Activities and Dams). The model shows the confluence of some common pressures to these sources, and especially of common impacts through which they exert impact and of ecological endpoints which are in many cases found to be the same. All endpoints relate to three major aspects of an ecosystem: stability, biodiversity and natural productivity.

4. Discussion

4.1. Multi-metric index approach

Analysis of the pressure scores in the eight estuaries (at descriptor and component levels) allowed the identification of the most pressured systems and of the main pressures occurring in each system. To address the impact of these pressures in each site the natural vulnerability score of the estuaries must also be taken into account. Ferreira (2000) included a vulnerability component in his model of estuarine quality and condition, in order to assess the buffering capacity of a system to assimilate materials discharged into it, and to evaluate the role of internal processes compared to throughput. As in Ferreira (2000) the relevance of this component increases with the fact that, from a quality standpoint, estuaries pose a particular issue because of their dynamic nature.

Results show that the least vulnerable systems, Tejo, Sado, Douro, are also the ones where the pressures are highest, and that the most vulnerable systems, Guadiana and Mira, show the lowest pressures. Currently, these estuaries where higher pressures are found are the ones where these pressures potentially have least impacts. However, problems might emerge if significant human development occurs next to more vulnerable systems. For instance, Douro estuary, with its high flow and low residence time, is least vulnerable to human development when compared to the Guadiana. Although bigger in size, this southern estuary has different characteristics which hinder its tolerance to human impacts and if a scale of development equivalent to the Douro's were to occur there, severe problems may be expected.

The combined use of the multi-metric index with the Principal Component Analysis identified groups of estuaries similarly affected by anthropogenic pressures. The results of the index ranked the estuaries in terms of total pressures, and identified the most active sources in each system. The ordination pattern obtained in the PCA outlined similarities among estuaries in terms of pressure components to which they are subjected.

The Tejo is the most pressured estuary; together with the Douro they are strongly influenced by the population and industry pressure components. These estuaries are located next to the two largest cities in the country, which explains the influence of this component vector in the PCA. The areas surrounding the Tejo estuary are inhabited by close to 2 million people and those surrounding the Douro by 700,000. Around the Tejo estuary there are close to 18,000 industries that produce yearly circa 75.5×10^6 m^3 industrial loads. In past decades, industrialization has developed in most estuarine areas and it is noticeable that industry is more relevant in the north while the southern estuaries have a higher agricultural influence.

Only 52 % of the population in the Douro's watershed is served by a sewage treatment network, as an example of the contributing factors to the poor score obtained by this estuary in the waste water treatment descriptor. Only the Ria de Aveiro had a higher score here. The Tejo estuary has the highest score for water and sediment quality, with highest nitrogen and phosphorus loads (average 23,639 ton $year^{-1}$ and 6594 ton $year^{-1}$) and also presents poor sediment quality, according to Long et al. (1995) with Hg and Zn concentration above the Effects Range Medium and Cd, Cr, Cu and Pb above Effects Range Low. Alongside the Tejo, the Sado and the Ria de Aveiro estuaries are the most problematic in terms of metal contamination.

The Douro estuary has a remarkably negative influence from dams, since the dam situated furthest downstream, built in 1985, is located only 20 km from the estuary mouth, and transformed the dynamics of the estuarine system, creating an artificial limit to saltwater intrusion and to the estuarine head limit (Vieira and Bordalo, 2000). This is unique in the analysed set of estuaries and might explain the displacement of the Douro towards the dam vector in Fig. 4.

Port activities and dredging appear associated in most of the systems, probably due to the fact that dredging is required in many of these systems in order to maintain navigation canals. It is also a strong component contributing to high pressures in the Tejo and Douro estuary. The port of Lisboa situated in the Tejo estuary is the second biggest port in Portugal with commercial traffic averaging 3689 ships per year (37×10^6 tons gross tonnage) and dredging activity is intense in both estuaries. In the past years up to 1.5×10^6 m^3 of sediments were extracted yearly in the Douro and this volume has increased due to the construction of jetties at the mouth of the estuary.

It is interesting to note that the two coastal lagoon systems, Ria de Aveiro and Ria Formosa, present similar overall pressure scores originated by similar pressure types and intensities. Together with two other systems, the Sado and Mondego, they are most pressured by resource exploitation and port activities. In fact, the Sado and the coastal lagoons form a close group in the ordination plot. Although the Mondego is affected by the same sources, they are of lower intensities and that may explain its placement in the PCA.

Resource exploitation, namely fishing and aquaculture are very intense activities in these estuaries. Fishing is a traditional activity mainly undertaken by fishers with small boats using gill and trammel nets, and also traps in Ria Formosa. Ria de Aveiro has the highest score in the fishing descriptor. The number of active boats there is more than double of the one found for the Sado.

Both coastal lagoons and the Sado estuary present favourable features for the placement of aquacultures, mostly in former intertidal flats or saltmarshes. These are strongly set activities occupying 289 ha in Ria Formosa, 313 ha in Ria de Aveiro and 519 ha in Sado. With around 1000 ha of shellfish farms, Ria Formosa is renowned for its shellfish production.

Apart from the Douro and the Guadiana, most estuaries are affected by agriculture. One of the main agricultural productions in estuaries is rice, namely in the Sado and Mondego, which is associated with a high use of pesticides and fertilizers.

Aquaculture and agriculture strongly contribute to high scores of estuarine bank regulation as they, preferentially, claim saltmarsh areas. River embankment is also strongly contributing to bank regulation in Mondego estuary, as is urban occupation and stabilization of estuarine margins in the case of Douro and Tejo estuaries.

Port activities in the Ria de Aveiro and Sado are due to their important ports with commercial ship traffic areas and also in case of the Ria de Aveiro and Ria Formosa consequence of their intense recreational traffic.

The Guadiana estuary, a low pressured system, owes its score mainly to the dam component, where it has the second highest score but shows low scores on the other components.

The Mira estuary can be considered weakly impacted. It obtained the lowest score and is located in the opposite direction of the pressure vectors in the ordination plot. Agriculture is the main pressure source here, including its contribution to the destruction of saltmarsh areas and intertidal flats. Contrary to all other estuaries, it is located next to a small village with low intensity activities in and around the estuary.

4.2. Advantages of the multi-metric index approach

The multi-metric index approach revealed itself as a valid tool to assess the anthropogenic pressures on these estuarine systems and to find similarities between them in terms of affecting pressures. It allowed graphic analysis of the contributions of the pressures descriptors that compose the final index and also the running of multivariate statistic analysis which established similarities and confirmed pressure patterns between the estuaries.

One should take into consideration that the index is determined through comparison of a set of estuaries. Results obtained for each system are relative to, and dependent on, the set of estuaries considered, or to reference values that might be established, since the calculation of the metric, descriptor and component pressure scores use the minimum and maximum of each metric for the normalization of the different units. Therefore, as in Ferreira (2000), this methodology was not designed as a management tool for one particular estuarine system, which would need a different approach focussing on specific problems and potential solutions, but as a global approach establishing priorities for each location based on equivalent criteria and data resolution. However, data used in this study is capable of providing an in depth characterization of each system.

Good results obtained with the present approach to this group of estuaries suggest that the same methodology could be applied on a different scale provided that other necessary metrics and case specific descriptors are incorporated. Considering the EU WFD aims to prevent deterioration in all bodies of surface and ground water, it would be an interesting tool to evaluate and compare the pressures of a broad and heterogeneous set of estuaries, since as stated by Rogers and Greenaway (2005) healthy ecosystems can only be achieved by managing specific human activities and the extent to which they affect different components of the environment. Great effort in data collection, and descriptor uniformity would be necessary to compare different European systems. A baseline of reference values could be generated so that all estuaries would be equally classified based on thresholds for well-preserved and deteriorated environments, granting a view on the relative importance of pressures found in estuaries within the European context.

Reference conditions are particularly hard to define and general consensus must be achieved for their establishment. Within the Portuguese context the Mira estuary, despite its high natural vulnerability, is currently a possible model for establishing standard references for low levels of disturbance and this is taken in to consideration in this analysis.

The index is very versatile, easily updated with the introduction of new data or metrics and annual or seasonal results for pre-defined metrics can be used to follow evolution through time.

As in many studies using indices, data compilation for all descriptors or indicators and meeting the assessment criteria represent the biggest challenges. Data use was limited by availability for the estuaries and was restricted to guarantee that the same data resolution was used in all estuaries. In this approach, pressure descriptors were not previously defined, their election was based on indicators used in similar studies (Boesch, 2000; Ferreira, 2000; Brown et al., 2002; Paul, 2003; Marques et al., 2004; Serveiss et al., 2004; Borja et al., 2006). Elected metrics are of importance to this set of estuaries, and descriptors of reduced relevance that would bias the analysis were discarded.

Achieving a consensus in opinions regarding the relative importance of indicators, which would allow for a correct weighing of indicators, has generally been proven difficult to achieve (see Aubry and Elliott, 2006). Due to a lack of data and knowledge on which to base this process and in order to avoid subjective judgment or classifications indicators were not given weights.

While other indices have been criticized for loss of detail due to aggregation (Brown et al., 2002) with the presented methodology these problems are surpassed by the determination of intermediate pressure values, i.e. metric, descriptor and component scores, which are progressively aggregated. This allows the characterization of the estuaries in terms of several pressure types, in a way that high or low overall index values can be easily traced back to the responsible source.

4.3. Anthropogenic pressures and influence on nursery fish species

After assessing the anthropogenic pressures on these estuarine systems, a CA evaluated how human activities influence the fish species that use these estuaries as nursery areas.

This CA suggested that the separation of estuaries and species defined by their different abundances is not coincident with any pressure pattern. There is no evident direct link between a pressure and a species. The link between the anthropogenic pressures assessed and nursery fish species is not established directly, instead given the general use pattern of the species in these estuaries, as outlined with the CA and the intensity of pressures, as given by the index, a series of consequences can now be drawn.

The occurrence and densities of the dominant species that use these estuaries as nursery areas greatly differ as well as the anthropogenic pressures they are subjected to. Species that use a group of estuaries are potentially affected by different pressures from another group of species using a different set of estuaries. The latitudinal gradient and separation of estuaries observed is due to the fact that some of the species present have northern or southern affinities, especially as this coast is recognized as a transition area between zoogeographic regions (Cabral et al., in press). Seabream species which have a stronger presence in southern estuaries (especially in Mira and Ria Formosa), are more exposed to pressures generated by agriculture and aquaculture activities and less to population and industry originated pressures, particularly *D. annularis* which only uses the Ria Formosa as a significant nursery. On the other hand, flounder, which almost exclusively occurs in estuaries in the north, coexists with opposite pressures depending on the system, from population and industry sources, very intense in the Douro estuary, to resource exploitation and port activities related pressures in Ria de Aveiro and Mondego. The common sole, senegalese sole, sea bass and sardine have widespread distributions and are exposed to a broader range of pressures.

4.4. Ecological conceptual model approach

Most of the anthropogenic activities listed have specific actions on the ecosystem, particularly when analysed in terms of estuarine-dependent fish nursery areas. Index results clearly state that there are dominating groups of pressures but seldom is there one type of activity acting in isolation, or responsible for all negative impacts in the estuary. It is therefore fundamental to address this issue in a holistic manner, understanding the impacts and interactions between all kinds of anthropogenic activities, their direct and indirect consequences and making predictions on their implications in terms of the natural importance of estuaries as fish nursery areas.

Additionally, this information should be applicable in establishing future management actions, as well as a basis for the coordination of future scientific studies.

A properly developed conceptual model effectively captures the scientific understanding of an ecosystem and its response to natural and anthropogenic pressures. In this sense, and following Gentile et al. (2001), the presented model was built considering that it should be developed specifically for these ecosystems and their associated environmental problems. In these estuaries a multitude of anthropogenic sources was found. However their pressures, impacts and ecological endpoints are in some cases coincident, with the latter related to three major aspects of an ecosystem: stability, biodiversity and natural productivity.

The gathered information was adapted and synthesized in the model, establishing the way each source affects a system. Water quality in estuaries is often altered and threatened by the excessive load of nutrients, organic matter and contaminants. Nutrients and organic matter inputs are responsible for causing eutrophication which is linked to hypoxia and anoxia. These decrease habitat quality of juvenile fish, restrict them to oxygenated areas, contracting suitable habitat and possibly promoting density dependent growth rates. Intermittent events of anoxia are also common, decreasing benthic prey availability (Eby et al., 2005; Powers et al., 2005).

Chemical contaminants, as trace metals, hydrocarbons and synthetic organ compounds, are renowned for their effects on living organisms, namely lethal, sublethal, chronic, genotoxic, cytotoxic which promote toxicopathic and infectious diseases, reproductive impairment, growth dysfunctions and mortality (Johnson et al., 1998; Marchand et al., 2002). These can be felt at several levels of biological organization from biochemical to population or community responses (Chapman, 1990; Long et al., 1995; Bolton et al., 2004).

Habitat loss has probably the most significant impact on fish, especially by bank regulation and reclamation. These have a direct effect on estuarine intertidal mudflats, seagrass and oyster beds, saltmarshes, and other habitats that act as important nursery and feeding grounds for fish (Mclusky et al., 1992; Beck et al., 2001). Reduction in habitat complexity, variety and spatial heterogeneity can have multiple consequences. Juveniles may not be able to reach suitable grounds, leading to starvation, decreased growth, increased mortality and to direct results in terms of population and potential production with lower recruitment success. Habitat destruction has far reaching consequences. Besides altering food webs, it can modify the structure and function of estuaries contributing to the decline in biodiversity (Peterson, 2003).

Freshwater flow into estuaries is significantly controlled by damming which changes the salt wedge as well as upper limits of estuaries. For fish species that use estuaries as nurseries, alteration in salinity conditions may lead to the loss of the natural conditions that promote juvenile growth and survival and loss of suitability and productivity of feeding grounds, by placing optimum range salinities where essential or suitable habitat is not found (Peterson, 2003). Changes in either direction of freshwater flow cause shifts in biotic community structure and production, influencing trophodynamics and fisheries (Jassby et al., 1995; Wagner and Austin, 1999; Peterson, 2003). Dams constitute major obstacles to diadromous species not only due to the physical obstruction of fish passage upstream but also due to modifications of estuarine conditions and hydrodynamics affecting fish entrance to the estuary (Costa et al., 2002a). Besides this, damming is also responsible for a significant retention of sediments, which strongly alters sediment dynamics in estuaries and aggravates coastal erosion affecting the natural protection of the system.

Direct removal of invertebrates or fish by fishing can compromise the success of particular fish species, age-groups or certain trophic levels of the community (Blaber et al., 2000). Although Boreman (1997) outlined that in earlier life stages fish are typically more sensitive to environmental changes, while fishing mortality occurs in older age groups, in these estuaries fishing activities may have deleterious effects on juveniles, compromising the estuarine nursery potential. This is due to fisheries that target juveniles and others with high by-catch rates such as beam trawl and fyke nets. Another important aspect of estuarine fisheries is that they target diadromous species. This is particularly deleterious since they catch either juveniles or mature fish on their way to spawning grounds. In the Portuguese case, some diadromous fishes have high commercial value, namely glass eel, *Anguilla anguilla* (Linnaeus, 1758), and sea lamprey, *Petromyzon marinus* Linnaeus, 1758, and are illegally intensively fished.

Ultimately, high mortalities associated with fishing can affect the composition and trophic relationships of the ecosystem, and damage its nursery and production capacity (Blaber et al., 2000; Sobrino et al., 2005).

The conceptual model outlines what links are relevant as well as the main uncertainties about an ecosystem, allowing scientists and decision-makers to prioritize areas for research (Gentile et al., 2001). Furthermore, the model can be resumed to sources and ecological endpoints which add to practical value since managers require holistic answers in concise manner, without a high level of detail (Elliott, 2002). The consequent management objectives should be directly linked to scientifically measurable endpoints in order to assess and compare the ecological condition (Suter, 1999; Gentile et al., 2001) and establish suitable monitoring programs.

With the implementation of the EU WFD each member must decide which, and how many, water bodies will be monitored to assess long term changes within each river basin. The presented model is an adaptation of the DPSIR framework (Driver Pressure State — Change Impact Response) adopted by the European Environmental Agency (Elliott, 2002) and together with the multi-metric index, these should contribute for the definition of conservation and management priorities for these estuaries as established in the WFD objectives, within the specific scope of this work. The combined results of the current assessment should assist in preventing further degradation in these systems, in order to achieve at least 'good ecological quality status' by 2015, since it identifies and compares the main pressure sources as well as their expected impacts on one of the most important ecological function of estuaries.

4.5. Scenario analysis

The model illustrates the impacts potentially found in this set of estuaries of the Portuguese coast according to the relative strengths of pressures obtained by the multi-metric index approach. As large differences are found between estuaries regarding main pressure types, different potential impacts and consequent ecological end points are expected. The associated monitoring and suitable management directives will also be diverse, so different scenarios can be generated from this conceptual model and are now briefly discussed.

4.5.1. The Douro estuary

The Douro estuary is mainly influenced by population, urban pressures and industrial development. The prevailing effects are those related to chemical pollution and nutrient enrichment, causing contamination to organisms and deterioration of water and sediment quality. In fact, the Douro has the second highest score for water and sediment quality (0.64) only surpassed by the Tejo. High natural vulnerability results obtained for the Douro estuary show that it may have lower probabilities of having serious water quality problems. Nevertheless this does not mean that it will not be affected by the main pressure sources.

With the aid of the conceptual model, one can establish the targets and priorities for scientific research and management in the Douro estuary. They should, for instance, focus on nursery function and productivity, as well as analyse the condition, contamination, growth and survival rates of these juveniles. Currently there is a lack of studies in terms of nursery function of this estuary, and little information in terms of biological contamination and its effects, namely on juvenile fishes of *P. flesus*, *S. solea* and *D. labrax*. On the other hand, efforts should be made to diminish untreated and direct sewage and industrial effluent discharges into the estuary. This is mostly dependant on management options and decision makers and is imperative with the implementation of the WFD, since it specifically states objectives concerning the reduction of discharges and urban waste water treatment.

Dredging will contribute in terms of chemical pollution due to the resuspension of contaminants, mainly affecting the benthic communities (Marchand et al., 2002). Knowledge of these communities, as well as of the effects produced on them by dredging, is fundamental since these organisms are vital for the success of juvenile fish, as they are a common prey for most species, namely flounder and soles. In fact, prey availability is recognized as one of the key aspects in nursery areas (Haedrich, 1983; Gibson, 1994).

Considering the Dams score (0.66) and the inevitable effects of a dam situated at less than 20 km from the mouth of the estuary and its control on river flow, a well based scientific knowledge on the influence of freshwater flow on the estuary is necessary. Specifically, studies should be directed to fish assemblage, nursery areas and entry of diadromous species like eels, shads and lamprey, and their effective passage upstream. In terms of flow control, management options should take these ecological aspects into consideration.

4.5.2. The Ria de Aveiro, Ria Formosa, Mondego and Sado estuaries

The analysis revealed a group of estuaries largely associated with resource exploitation (agriculture and aquaculture) and port activities. Considering the obtained scores and following the conceptual framework established by the model, the Ria de Aveiro, Ria Formosa, Mondego and Sado estuaries will be mostly influenced by the effects of bank reclamation, loss of habitat and by fishing mortality.

Loss of habitat is one of the most significant effects on an estuarine system. Occupation and destruction of saltmarsh areas by agriculture and aquaculture denies the use of these habitats to juvenile fish. In addition, both these activities have their own impacts on these systems, contributing to nutrient enrichment and chemical pollution. Episodes of eutrophication and seasonal algal blooms are commonly reported for the Mondego estuary (Marques et al., 2003).

Monitoring loss of habitat is essential in maintaining the nursery function of an estuary. Scientific studies should evaluate the importance of existing habitats in terms of prey availability and juvenile fish densities. Decrease in densities should be interpreted as a sign of diminished natural productivity and nursery function. Management efforts should be made to control further expansion of reclaimed areas and before deeming an area as exploitable it is essential to evaluate its ecological importance. In the Mondego estuary the area occupied by *Zostera noltii* (Hornem, 1832) decreased from 150,000 m^2 to around 200 m^2, in a single decade, due to several factors, including eutrophication or human disturbances from macroinvertebrate harvesting for fish bait. Only then was a program for preservation, restoration and transplantation of *Z. noltii* implemented (Marques et al., 2003; Martinho, 2005). The effects of this depletion of seagrass beds on fish communities have not been addressed in this and other Portuguese estuaries.

There are no previous studies of the Mondego as a specific fish nursery and only recently Martinho (2005) assessed the importance of the entire estuary for this purpose. This example illustrates the lack of information in most Portuguese estuaries and the degradation they may be subjected to due to lack of scientific knowledge and management awareness.

Fishing is an activity common to all these estuaries but is particularly intense in both coastal lagoons, mostly directed at flounder, soles and sea bass in Ria de Aveiro and Mondego, and seabreams and seabass in Ria Formosa. Fishing activities must be analysed as a whole in order to assess direct mortalities but also to evaluate the relevance of unintentional mortality caused by by-catch and indirect impacts caused by substrate destruction. Besides professional fishing, it is necessary to evaluate the consequences of recreational fisheries. There is no information in terms of numbers of fishers or estimated captures. Although common to all systems, it is particularly problematic in both Ria de Aveiro and Ria Formosa, where the natural conditions favour this activity. In the future, efforts should be made to quantify and regulate recreational fisheries. Although fishing may have a significant effect on mortality of juvenile fishes and on success of recruitment to the marine stock these do not directly impair the estuarine nursery function. However specific gears like beam trawling do (Blaber et al., 2000).

4.5.3. The Tejo estuary

The Tejo estuary is affected by all sources of pressure and is an important nursery area for soles, sea bass and sea breams. Considering the previously analysed scenarios, similar approaches should be followed taking in consideration the particular aspects and results of this estuary. In the particular case of this estuary beam trawling is a common and legal activity targeting brown shrimp *Crangon crangon* (Linnaeus, 1758) and *Solea* spp. There are several problems related to the use of this fishing gear namely habitat destruction, associated mortality of benthic fauna, high juvenile fish mortality, including soles and sea bass, and high discards of other non-profitable species. Studies have addressed this issue and suggested management options to reduce their impact (Gamito and Cabral, 2003).

Monitoring migratory species' population and their reproductive success is essential since many are presently seriously threatened. In the past, colonisation occurred in most of the watershed, but presently few species remain (Costa et al., 2002a).

A major feature of the Tejo is its commercial port. This activity leads to chemical pollution and deleterious effects have been registered, namely the large scale decrease in oyster beds due to contamination by TBT (De Bettencourt et al., 1999). Another common effect due to ports is the introduction of opportunistic exotic species that are transported in ships ballast waters. These non-indigenous species can settle and displace indigenous species, some of which may even be of commercial value, reducing species diversity and changing the normal function of the ecosystem (Goldberg, 1995). It is essential to monitor species' composition and possible successful invasion by these opportunists to guarantee the stability of the ecosystem. Clearly the best way to prevent the import of toxic organisms is avoiding the release of ballast waters in ports. Several measures have long been suggested by Hallegraeff and Bolch (1991) to minimize this potential hazard while the International Convention for the Control and Management of Ships Ballast Water and Sediments, by the IMO (International Maritime Organization), is waiting to be ratified.

Of the considered estuaries the Tejo is the most studied in many aspects of its ecological functioning. This information should be a valuable advantage when establishing future study priorities and management proposals.

4.5.4. The Guadiana and Mira estuaries

The Guadiana and Mira are the least pressured estuaries. In the case of the Guadiana, studies should be focused on migratory species and on effects of freshwater regulation on fish communities and nursery areas, due to the strong influence from dams. A strong effort is already being directed to the influence of the recent construction of the Alqueva dam, namely on fish assemblages (Chícharo et al., 2006). The pressures the Mira estuary is subjected to are originated by agriculture and aquaculture. Besides controlling the expansion of these activities, assessments need to be made of the fish assemblages and nursery areas along the estuary in order to avoid loss of essential habitat for *Diplodus* spp, *D. labrax* and *Solea* spp.

Given the defined scenarios the challenge for scientists will be to establish criteria for minimum effects while managers must be able to satisfy these criteria through appropriate management options.

5. Final considerations

Kennish (2002) defined general tendencies for the progress of anthropogenic pressures. He suggested that habitat loss and alteration will have the most significant impact on estuaries and points out excessive nutrients and sewage inputs as a high priority problem. Overfishing is expected to become a more menacing and significant factor, whereas chemical contaminations will remain problematic and freshwater diversions are becoming an emerging global problem. Additionally changes in estuaries due to human action may imply consequences at a larger scale since estuaries and surrounding coastal areas are ecologically connected (Able, 2005; Beck et al., 2001).

Portuguese estuaries are poorly studied. Few have historical data series and the window of opportunity for obtaining quantitative baseline data is narrowing while estuarine habitats are being altered at a rapid rate (Peterson, 2003). Although impossible to characterize pristine conditions, it is fundamental to have strong sets of information on which to base decisions. It is imperative to build a baseline of studies covering a wide field of subjects that can offer a full view of the actual status of these estuaries, assess changes, predict trends and prevent future degradation while establishing viable management plans.

The results of this work, specifically the anthropogenic pressure assessments and the conceptual model, should prove valuable tools for the future preservation of Portuguese estuaries. The collected baseline information and the versatility of the index should lead to a better understanding of the problems affecting these estuaries, prioritizing scientific studies and targets, as well as establishing management plans to preserve their function as nurseries. For this task to be successful, the articulation between scientists and decision makers is of the utmost importance.

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