

# The contribution of scientific research for integrated coastal management: The Mondego estuary as study case \*

## *O contributo da investigação científica para a gestão costeira integrada: O estuário do Mondego como caso de estudo*

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### ABSTRACT

The present paper quantifies and summarizes the research performed in the Mondego estuary (Portugal) over the last decades. Online databases were used to quantitatively assess the international publications, the master dissertations and PhD theses focused in the research about that estuary, from 1989 to 2012. In general, there had been a notable growth trend in publication output. Estuarine, Coastal and Shelf Science was the most active journal publishing on Mondego estuary. Field studies were the predominant type of research and the population/community dynamics and functioning have been one of the main research topics. Towards the time, the estuary has been used as local for several studies and the existing database has been useful to test theoretical ecological hypotheses and to support some management decisions and ecosystem restoration schemes. The efforts intended to its preservations are justified by its high ecological value, presenting large diversity of habitats and biodiversity, and its socio-economic importance, providing goods and services to population. The published research results cover several aspects of the system including the hydrology, the nutrient cycling, the communities' structure, diversity and dynamics. Moreover, research focused in existing environmental problems like eutrophication, extreme climatic events and contaminants, characterizing them and proposing solutions. The Mondego estuarine water quality status, was also intensely studied especially in order to implement the Water Framework Directive. The Mondego estuary has suffered intense anthropogenic pressure and hydromorphological modifications over the last decades that induced a progressive decline in its ecological condition. In order to reverse the tendency of the ecosystem degradation a restoration project was implemented in 1997/98, followed by a more intensive intervention in 2006. Parallels, the estuary suffered the effects of climate changes that seems to masked the response of water quality and biological communities to mitigation measures. Although we are only at an early stage in the projected trends of global warming, ecological responses to recent climate change are already clearly visible in this shallow water temperate estuarine system.

**Keywords:** Mondego estuary, coastal management, research trends, science divulging and science management.

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**RESUMO**

O presente artigo resume a pesquisa realizada no estuário do Mondego (Portugal) ao longo das últimas décadas. Foi feita uma pesquisa em bases de dados de pesquisa online para avaliar quantitativamente as publicações internacionais, as dissertações de mestrado e teses de doutoramento sobre o referido estuário, entre 1989 a 2012. Em geral, houve uma tendência de crescimento notável na produção de publicações. A revista científica *Estuarine, Coastal and Shelf Science* foi a mais ativa a publicar estudos sobre o estuário do Mondego. Os trabalhos de campo foram o tipo predominante de pesquisa e a dinâmica e funcionamento das populações/comunidades tem sido um dos principais tópicos da investigação. Ao longo do tempo o estuário tem sido usado como um local para vários estudos e a base de dados existente tem sido útil para testar hipóteses ecológicas teóricas e para apoiar algumas decisões de gestão. Os esforços desenvolvidos para a sua preservação são justificados pelo seu elevado valor ecológico, pois apresenta grande diversidade de habitats e biodiversidade, e pela sua importância sócio-económica, facultando bens e serviços à população. Os resultados da investigação publicados abrangem vários aspectos do sistema, incluindo a hidrologia, o ciclo de nutrientes, a estrutura das comunidades, diversidade e dinâmica. Além disso, a pesquisa tem-se focado em problemas ambientais, como a eutrofização, os eventos climáticos extremos e os contaminantes, caracterizando-os e propondo soluções, bem como o estado de qualidade da água, especialmente na implementação da Directiva Quadro de Água. O estuário do Mondego tem sofrido intensa pressão antrópica e modificações hidromorfológicas nas últimas décadas que induziram um declínio progressivo na sua condição ecológica. A fim de reverter a tendência da degradação do ecossistema um projeto de recuperação foi implementado em 1997/98, seguido de uma intervenção mais intensa em 2006. Paralelamente, o estuário sofreu o efeito de alterações climáticas que parecem ter mascarado a resposta do ecossistema em termos de qualidade da água e das comunidades biológicas às medidas de mitigação. Apesar de estarmos apenas na fase inicial nas tendências projetadas do aquecimento global, as respostas ecológicas para mudanças climáticas recentes são já claramente visíveis neste sistema estuarino temperado.

**Palavras-Chave:** Estuário do Mondego, gestão costeira, tendência de investigação, divulgação científica, gestão de científica.

**1. INTRODUCTION**

The coastal zones are attractive for human populations resulting in complex patterns of exploitation of natural resources. The biodiversity supported by coastal areas plays a fundamental role in sustaining a wide range of goods and services, "defined as indirect or direct benefits to human society arisen from the natural environment" (Beaumont *et al.*, 2006) essential for the maintenance of our social and economic wellbeing (Costanza *et al.*, 1997; de Groot *et al.*, 2010). Nevertheless, the intense uses of those zones have caused disturbances from diverse order that compromise and threaten their integrity (Raffaelli *et al.*, 1996). Despite being the major part of the environmental impacts essentially local (as pollution and overfishing), its effects usually have regional and global consequences. Moreover, coastal areas are also target of global environmental disturbances (e.g. changes in temperature and in the precipitation regimes) (Sterr *et al.*, 2003; Morais, 2008; Ferreira *et al.*, 2008).

The complexity of interactions occurring in the littoral coast, its diverse use, socioeconomic relevance, and its high environmental value, justifies the attention given to the coastal action plans in the last years (Cicin-Sain & Belfiore, 2005; Rosa *et al.*, 2012; Almeida *et al.*, 2012; Oliveira & Nicolodi, 2012). Worldwide, those areas represent one of the biggest challenges for environment conservation. However, the sustainable use, development, and protection of the shoreline and the preservation/restoration of their resources are only possible through an integrated and coherent management (Cicin-Sain *et al.*, 1998; Cicin-Sain & Belfiore, 2005). Consequently, to effectively manage these areas is primordial to take decisions based on a robust scientific, technical and multidisciplinary background. So, it is very important the investment in research activities allowing a better understand of these valorous systems and develop methodologies and tools that will enhance our predictive

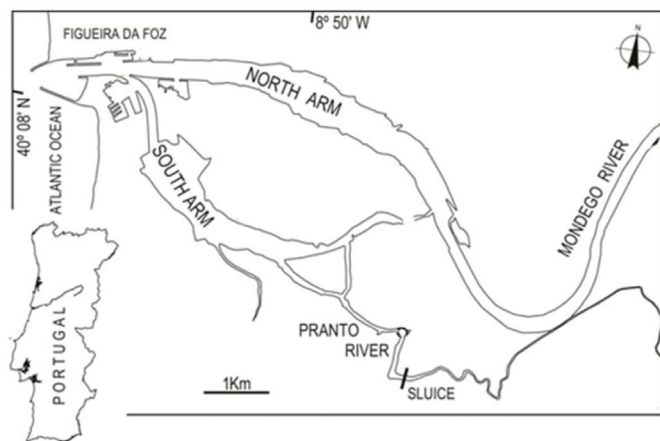
and management abilities. The priority is the understanding of the evolution of coastal systems under the influence of different scenarios. As Morais *et al.* (2008) referred, it is also important the application of precautionary measures that stabilize the level of resilience of the ecosystems, i.e., its ability to sustain self-organization in face of new situations of stress or shock.

Portugal is not an exception in facing the challenge of manage coastal zones, especially because it is a country with an extensive shoreline compared to its geographic area. Its coastline presents a wide geomorphological diversity from sandy stretches, ponds, rocky shore, coastal lagoons, and estuaries where important ecological and biophysical phenomena occur. Historically, the Portuguese trajectory has always been associated with the sea and the main urban clusters are in the coastal strip (Ferrão, 2006).

In Portugal, there are several universities with research groups developing competitive research on the littoral zones, particularly focusing on estuaries. It is well known that these coastal areas are among the most productive and valuable ecosystems of the world, supporting fundamental ecological links with other environments (Beck *et al.*, 2001; McLusky & Elliott, 2004; Costanza *et al.*, 1997; Boyd & Banzhaf, 2007; Jørgensen, 2010; Barbier *et al.*, 2011; Martinho *et al.*, 2012). Estuarine systems have long been regarded as stressed areas due to the high degree of variability in their physicochemical characteristics and human pressure (Kennish, 2002). It is also widely recognized the essential role of estuaries for life in the oceans, especially coastal platforms, serving as refuge and nursery areas of many marine species and as residency of several others (Cabral *et al.*, 2007; Martinho *et al.*, 2007a; 2012). Estuaries present also resting, nesting and feeding areas to native and migratory avifauna (Múrias *et al.*, 2002; Lourenço *et al.*, 2008; Burton *et al.*, 2010).

The Mondego estuary (Fig. 1) represents one of the Portuguese coastal zones for where interesting investigation

has been developed. In this context, the main objectives of the present work were: a) to quantify and qualify the scientific international publications and academic dissertations about the Mondego river estuarine system; b) to present an overview of the research conducted about this ecosystem emphasizing its main goods, services, constraints, and remediation measures implemented during the last decades.



**Figure 1.** Location and morphology of Mondego estuary.  
**Figura 1.** Localização e morfologia do Estuário do Mondego.

## 2. MATERIALS AND METHODS

The search for bibliometric assessment of scientific research trend reporting the Mondego estuary studies, published till December 2012, was performed through online databases and our own reprints collection. The online search for peer-reviewed journal articles was made on the multidisciplinary databases SciVerse Scopus from Elsevier and Web of Science from Thomson Reuters, using *Mondego estuary* as topic mentioned in the title, abstract or keywords. Additionally, a search in the RCAP - Repositório Científico Aberto de Portugal (Open scientific repository of Portugal) (<http://www.rcaap.pt/>) was performed with the same keyword to find master dissertations and PhD theses. All records were analysed individually to ascertain the number of documents that occurred in each databases. Additionally, our own reprints having the Mondego estuary as area of study were used to complement the information caught from the online database, namely the older publications and master dissertations and PhD theses. Mainly to the post-graduated works complementing with our knowledge was essential because a good part of the theses and dissertations were not available from the RCAP.

All the publications referring to Mondego estuary were grouped by year. Then, and despite the difficulty of publications classification, due to its transdisciplinary, they were quantified by type of research (descriptive/analytical, experimental or management studies). The descriptive/analytical studies category was subdivided according with the

main subject of research (population/community dynamics and functioning; nutrients/eutrophication; climate changes; contaminants; multiple stressors), and with main species groups (benthos; plankton, fishes; birds). Additionally, the impact factor (IF) of the journals was determined for each article as reported in the year 2011 by the Journal Citation Reports.

In order to pursuit the second objective of the present work, we revise and discuss the research conducted on the Mondego Estuary. We support our discussion not only in the publications quantified through the online databases reported above, but also in our knowledge of the system and in some national publications, conference reports, and book chapters. These last publications were not quantified in the bibliometric analysis due to the lack of online databases covering all them.

## 3. RESULTS

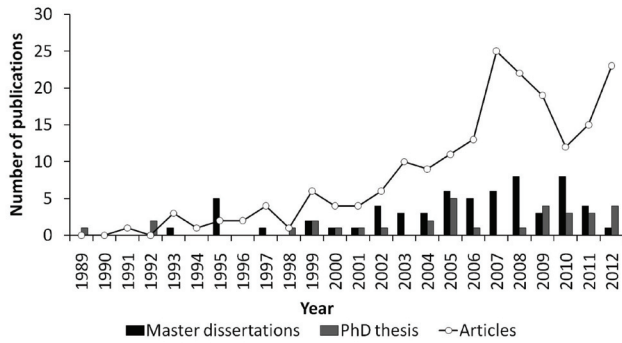
There is a wide database about the Mondego estuary available in the literature reporting more than 2 decades of research. The recoveries found ranged from 1989 to 2012, and included 193 scientific publications in international journals, 62 master (MSc) dissertations and 32 doctoral (PhD) theses (Fig. 2). Ninety one of the referred academic works were presented to the University of Coimbra and only 3 to the University of Aveiro (both Portuguese universities). It is important to underline that several other publications focused in the Mondego estuary have been disclosed in national journals, books, conferences and in national and international meetings, but as referred before, those were not included in the quantification.

Table 1 listed the top 5 most active journals producing articles on Mondego estuary including its IF. Totally, the 193 articles were published in 44 journals. Among those, 47.7% contained only one article, 13.6% contained two, 13.6% contained three, and 25.0% contained more than 3. The journals with more publications of Mondego estuarine studies were the Estuarine, Coastal and Shelf Science and Ecological indicators. The first published 22.3% of the total articles while to the second corresponded 11.4%. Considering all the 193 journals publishing Mondego estuarine studies, the IF ranged between 0.421 and 3.746 with a median of 2.247 and a mean of 2.013.

The trend of international publication was not stable during the years but, generally, increased and reached a peaks in 2007 with 25 articles published, followed by a decreasing until 2010 and a new increase afterwards (Fig. 2). The highest number of MSc dissertations occurred in 2008 and 2010 (8 publications), while the PhD theses reached the maximum of 5 in 2005. The number of articles published by year was positively correlated with the number of MSc dissertations (Spearman Rank Order Correlation,  $r=0.794$ ,  $p<0.001$ ) and PhD theses ( $r=0.451$ ,  $p<0.05$ ).

In general, the studies developed so far are diverse and can be divided in three main lines of research:

- studies of descriptive and analytical nature (composition, distribution, structure, and dynamics), characterizing the system or parts of it. Hereafter designated as descriptive/analytical studies;



**Figure 2.** Number of scientific publications in international journals and academic dissertations/theses focused on Mondego estuary, from 1989 until 2012.

**Figura 2.** Número de publicações científicas em revistas internacionais e dissertações/teses acadêmicas sobre o estuário do Mondego, de 1989 a 2012.

**Table 1.** The top 5 most active journals producing articles on Mondego estuary during the period of 1991–2012. IF-Impact factor.

**Tabela 1.** Os 5 jornais mais activos na publicação de artigos sobre o estuário do Mondego durante o período de 1991 e 2012. IF- Fator de impacto.

Journal	IF 2011	Nº articles
Estuarine, Coastal and Shelf Science	2.247	43
Ecological Indicators	2.695	22
Marine Pollution Bulletin	2.503	16
Hydrobiologia	1.784	15
Acta Oecologica	1.570	13

- studies of experimental nature, in the field or under controlled laboratorial environment, reproducing the Mondego estuarine conditions, using one or several species at the same time. Hereafter designated as experimental studies;
- studies focusing on development of tools/methodologies for environmental monitoring, assessment, and management (ecological indicators, indices and models). Hereafter designated as tools development studies.

The studies of descriptive and analytical nature are the more abundant group, with 127 publications against 14 of the category experimental studies and 52 of development of methodologies for environmental monitoring, assessment, and management (Table 2).

To a better understanding of the research trend over time of the types of research and the main areas of field studies, Figure 3 was developed. It can be observed that the papers focusing in the population and community structure and functioning, present the higher number of

**Table 2.** Number of international publications about the Mondego estuary organized by main type of research and main subject.

**Tabela 2.** Número de publicações internacionais sobre o estuário do Mondego organizadas por tipo de investigação e tema.

<b>Articles about the Mondego estuary</b>	<b>193</b>
<b>Field studies</b>	<b>127</b>
• Population/community dynamics and functioning	67
-Benthos	31
-Fishes	19
-Plankton	11
-Birds	6
• Nutrients/Eutrophication	22
• Climate changes	12
-Benthos	3
-Fishes	3
-Plankton	6
• Contaminants	9
• Multiple stressors	6
• Others	11
<b>Experimental Studies</b>	<b>14</b>
• Field	5
• Laboratorial	9
<b>Tools development studies</b>	<b>52</b>
• Modelling	17
• Indices/indicators	35

scientific publications (Fig. 3B). This topic corresponded to the first register in international journals and continues to be developed. From 1996, the nutrients dynamics and the eutrophication problem start to appear in the international scientific literature about the Mondego estuary. In 2001 one scientific article about contaminants was published, but only four years later (2005) this theme was taken up again for international publication. The effects of extreme climatic events in the estuarine ecosystems (climate changes category) were focus of attention from 2007 to 2011 and multiple stressors (referring to the articles that performed a joint analysis of eutrophication and extreme climatic events) were published between 2005 and 2012. During the long years of international publications others works were published punctually reporting diverse subjects like biochemistry, histology and physiology of some estuarine species (11 articles). The majority of the papers are focused in the biological integrity of the macroinvertebrate communities and in the estuarine water quality.

In respect to the research work developed in order to obtain a post-graduated academic degree, the main areas of the dissertations and theses (Table 3) belonged to the Biology/Ecology category. The other areas included only small amount of studies. Three of the master dissertations had a pedagogical approach. It is important refer that in Portugal the master and doctoral programs evolved in the last years to the Bologna model. The masters programs (24 months) have a first stage with one curricular year and a second stage devoted to supervised research. The doctoral programs have 48 months with a first stage with one curricular year and a second stage (36 months) devoted to supervised research. Before the implementation of the Bologna reform the doctorate did not included a curricular year.

**Table 3.** Number of master (MSc) dissertations and doctoral (PhD) theses by scientific area.

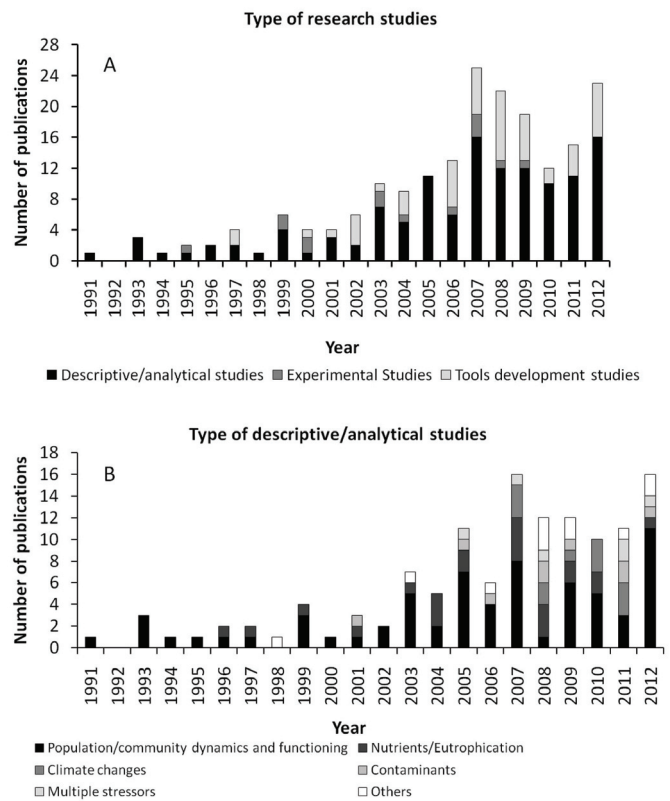
**Tabela 3.** Número de dissertações de mestrado e de teses de doutoramento por área científica.

	MSc	PhD
Biology/Ecology	55	26
Civil engineering	1	1
Geosciences	1	
Geography	1	2
Analytical quality control	1	
Chemistry		2
Environmental technology	1	
Marine and Coastal Sciences	2	
<b>Total</b>	<b>62</b>	<b>31</b>

## 4. DISCUSSION

### 4.1. Overview of the research output

To the coastal zone management is implicit a good knowledge of all interactions happening among the ecosystems' elements and it has been the goal of researchers in the Mondego estuary. It is our conviction that this objective was, in part, already accomplished because a lot of results concerning several aspects of the systems were already published. The research has achieved a suitable level of detail since the early 1990s, and a large amount of information is available in the literature. The areas of research were diverse and included various biogeochemical aspects of the system. Many studies were descriptive providing baseline knowledge important to posterior works while some were experimental, allowing the control of variables enabling the establishment of cause-effect relationships, and others permitted the development of tools and methodologies mainly addressing environmental quality of the estuary.



**Figure 3.** A) Number of international publications about the Mondego estuary by type of research study and by year. B) Number of descriptive and analytical studies published in international journals by main subject and by year.

**Figura 3.** A) Número de publicações internacionais sobre o estuário do Mondego por tipo de investigação e por ano. B) Número de estudos descritivos e analíticos publicados em revistas internacionais por assunto e por ano.

The biology, dynamics, and production of key species including zooplankton, algae, seagrasses, crustaceans, gastropods, bivalves, fishes, and birds are well described for this Portuguese estuary, at spatial and temporal scales (as reviewed in the next sections). A good part of the publications are the result of student's research during their post-graduation, which reveals students' interest in studying estuarine/marine topics contributing to its sustainable management. In the acknowledge sections of the articles was frequently mentioned the post-graduated grants that supported the work, which reveals the investment in the formation of human resources to be able to deal with marine and coastal problems. The positive correlation between the number of articles and the MSc dissertations and PhD theses found, can be explained by the fact that the academic works recorded were based on articles published in scientific journals, as mentioned by them. The multidisciplinary and transdisciplinary nature of the articles is noteworthy as is the quality of the research attested by the publication in recognized indexed journals, as also proved by the impact factor of the top 5 journals more active in publishing studies reporting the Mondego estuary (Table 2).

Part of the research published so far is included in programs that monitor estuarine macrobenthic, zooplanktonic, and nektonic communities, as part of projects financed by national institutions like the Fundação para a Ciência e Tecnologia (Foundation for Science and Technology), Instituto Nacional da Água (National Water Institute), and Instituto Interdisciplinar de Investigação (Interdisciplinary

Research Institute) (Table 4). The projects were mentioned frequently in the articles. The developed research so far has been developed at the interface of those ecosystem components relating, for instance, planktonic larvae and adults of either fish (Primo *et al.*, 2012) or crustaceans (Viegas *et al.*, 2011).

**Table 4.** Some of the projects developed on Mondego estuary with national financial support.

FCT - Fundação para a Ciência e Tecnologia (Foundation for Science and Technology); INAG - Instituto Nacional da Água (National Water Institute); III - Instituto Interdisciplinar de Investigação (Interdisciplinary Research Institute); JNICT - Junta Nacional para a Investigação Científica e Tecnológica (National Board for Scientific and Technological Research.); FEDER - Fundo Europeu de Desenvolvimento Regional (European Fund for Regional Development).

**Tabela 4.** Alguns dos projectos desenvolvidos no estuário do Mondego, com financiamento nacional. FCT - Fundação para a Ciência e Tecnologia; INAG - Instituto Nacional da Água; III - Instituto Interdisciplinar de Investigação. JNICT - Junta Nacional para a Investigação Científica e Tecnológica; FEDER - Fundo Europeu de Desenvolvimento Regional.

Title	Duration	Reference	Funding
Mondego estuary: Term evolution of the benthic communities and impact of excessive nutrients release	1993-1995	PBIC/C/MAR/1301/92	JNICT
Evaluation of ecosystem integrity saltmarsh ( <i>Spartina maritima</i> ) in the Mondego estuary, from the structure and function of the benthic reproductive processes	1996-2000	PRAXIS XXI/BD/9290/96	JNICT
Assessing key loss due to eutrophication in the Mondego and Mira estuaries	2001-2005.	POCTI/2000/BSE/36087	FCT
Characterization of the Mondego River estuary and establishment of management scenarios in terms of water quality and ecosystem integrity	2002-2004	---	INAG
DYNAMOD - Dynamic model of stress induced changes on biological communities	2002-2004	POCTI/MGS/37431/2001	FCT
The fishery resources within the European policy of sustainable development: an interdisciplinary approach to the case of sea bass ( <i>Dicentrarchus labrax</i> )	2005-2007	III/AMB/4/2005	III
EFICAS - Effects of natural stress generated by freshwater discharges in the benthic invertebrate estuarine communities and its influence on the assessment of the benthic ecological status	2005-2008	POCI/MAR/61324/2004	FCT
RECONNECT - System dynamic response to an ample artificial RE-establishment of the upstream CONNECTION between the two arms of the Mondego estuary (Portugal): Implications for recovery, ecological quality status, and management	2008-2011	PTDC/MAR/64627/2006	FCT
An integrative study on the toxicopathic lesions in Portuguese estuarine fishes - Assessing injury impact and toxicogenomic implications in experimental models	2009-2011	PTDC/MAR/70436/2006	FCT
3M-RECITAL - Minho, Mondego and Mira observatories: Variations of the state long-term ecological pressures caused by natural and human. implications in the management and recovery	2010-2012	LTER/BIA-BEC/0019/2009	FCT FEDER
BIOCHANGED - Impact of biodiversity evenness changes in the ecosystem functioning of estuaries	2011-2013	PTDC/MAR/111901/2009	FCT
COMPARE-Impact of climate variability on zooplankton community structure and function in estuarine ecosystems	2012-2014	PTDC/MAR/121788/2010	FCT

Besides the first publication in an international journal (according to current models of scientific publishing) to be only found in 1991 (Marques & Nogueira, 1991), preliminary surveys in the Mondego estuary begun in 1985 in order to plan the first more concrete studies (Marques *et al.*, 1999). Up to date, the research never stopped and consists in multidisciplinary approaches aiming the estuarine ecosystem characterization under the different points of view (hydrological, sedimentological, biological and ecological). Between 1993 and 1997 the studies focused mainly in a particular area of the estuary – the south channel (Fig. 1), which was considered not enough to characterize the whole system and in 2003 an extensive monitoring program was initiated on a monthly base including 23 stations uniformly distributed inside the Mondego estuary and 2 stations located next to the main fresh water discharges (Mondego and Pranto Rivers) (INAG, 2007).

#### 4.2. Characterisation of the Mondego estuary

The Mondego estuary (Fig. 1) is an intertidal estuary located in the western coast of Portugal (40°08'N, 8°50'W), in a warm temperate region, with a continental temperate climate. The estuary receives the flow of the river Mondego which source is located at Serra da Estrela and extends along 227 Km, draining a hydrological basin of approximately 6670 Km<sup>2</sup> (Marques *et al.*, 2002; Cunha & Dinis, 2002). Before the construction of several dams during the decade of 1970, the fluvial regimes were directly controlled by the seasonal precipitation in the catchment basin. Following the construction of two main dams in the Mondego river, the fluvial regime was smoothed, reducing slightly the freshwater discharge (Cunha & Dinis, 2002).

At the most upstream of the basin, the extractive industries play a key role for local communities. Downstream, other industries become predominant related with aquaculture, fisheries and paper production (Pinto *et al.*, 2009). In the margins of the terminal part of Mondego river were established several population clusters, being the more important the Figueira da Foz city in the estuarine mouth. The population established around the estuary is estimated in 63372 individuals (Pinto *et al.*, 2011).

The Mondego estuary extends for 26 km length and in its last 7.5 Km is divided into two arms/channels (south and north) in its terminal part, separated by the Murraceira Island (Cunha *et al.*, 1995). The arms present very different hydrological characteristics. The north arm is deeper (5-10m during high tide), receiving most of the marine tidal water and most of the fresh water from Mondego River constituting the main navigation channel supporting the Figueira da Foz harbour. The south arm is shallower (2-4m deep), almost silted up in the upstream areas and characterised by large areas of exposed intertidal flats during low tide. It receives freshwater from the Mondego and from the Pranto River. This last tributary has the discharge controlled by a gate located 3 km upstream of the mouth. The difference in depth between the two arms determines a faster propagation of the tide in the north arm causing higher daily salinity variations. According to Cunha & Dinis (2002), the propagation of the tide reaches 24 km upstream from the mouth.

#### 4.3. Mondego estuarine ecosystem goods and services

The value of the Mondego estuarine resources, highlighted by the research undergone during the last years, was economically measured by Pinto *et al.* (2009, 2010, 2011). Many goods and services are provided by the system, mainly for the Figueira da Foz, because this city has been intimately connected to the Mondego estuary through the economic activities. Besides, some of the goods and services could be attributed a monetary value. Nevertheless, the majority of other key estuarine services do not lead to marketed outputs. These include many services arising from ecosystem processes and functions that benefit largely human beings, such as coastal protection, nutrient cycling, erosion control, water purification, and carbon sequestration (Barbier *et al.*, 2011). One important service provided by Mondego estuary is the food production, not only by providing fishes, crustaceans, and molluscs to local inhabitants, but through the maintenance of fisheries. The Mondego estuary provides coastal breeding and nursery habitat for important commercial species (Martinho *et al.*, 2007a). In this regard, Pinto *et al.* (2010) suggests that Mondego estuarine ecosystem makes a significant contribution to society in terms of fisheries (7,078,000-14,831,000€). For this reason, it is essential take management actions towards protecting the habitats in the Mondego estuary that contribute to supply adult populations.

The value of Mondego estuary also involves an important cultural component (e.g. aesthetic, educational, scientific, and artistic). For instance, the valuable natural heritage of this ecosystem can be an attraction for the development of sustainable tourism activities by complementary to beach tourism (Cunha & Dinis, 1997). In fact, the tourism/recreation activities in the Figueira da Foz, which the impacts are mostly significant during the summer, have relevant social and economic importance representing 8,102,000-12,821,000 € (Pinto *et al.*, 2010). Over the years, a progressive increase in the number of tourists visiting the Mondego estuary and adjacent areas occurred and, consequently, the number of facilities provided for them (Dias *et al.*, 2008; Pinto *et al.*, 2010). Diverse infrastructures have been constructed increasing the supply of activities for tourists, not only in the city of Figueira da Foz, but also in the Mondego estuary, especially in the Murraceira Island. In this estuarine area, there was also a decrease in the activity of the primary sector, reflecting the abandonment of activities such as agriculture and commercial fishing combined with an important increase of provision of services, mainly in the forms of tourism and recreational activities (Pinto *et al.*, 2010). That alteration of activities practiced in and around the Mondego estuary must be seen with caution because the increasing of tourists in the Figueira da Foz results in the increasing human pressure into the Mondego estuary in many ways. For instance, along with beach activities, many summer tourists, besides local habitants, usually go to the intertidal areas of the estuary, to capture benthic invertebrates (Crespo *et al.*, 2010). This can originate a possible cause for the decline of some species like the common cockle *Cerastoderma edule*, which is used as food resource, or such as polychaetes that are captured to be used as bate in daily fisheries.

Aiming to implement a segment of tourism that uses

the natural and cultural heritage, some ecotourism projects have been developed in that area, like the ones aiming to contribute to the revitalization of saliniculture. The ecotourists could benefit from diverse opportunities like leisure, bird-watching, taste halophytes *in situ* and observe the traditional salt-extraction process *in situ* and within in an ecomuseum. Those activities claim to promote socioeconomic development preserving the ecological processes and the welfare of the populations involved. It is important to refer that the Mondego estuary contributes with 75% of visitors that are interested in ecotourism activities (Pinto *et al.*, 2010).

The revitalization of saliniculture promoted by the ecotourism, from the ecological point of the view, could be regarded as a minor pressure compared to others because salt ponds are important and threatened feeding habitats especially for migratory and wintering waders in the Mondego estuary (Lopes *et al.*, 2000; Múrias *et al.*, 2002). The loss of feeding opportunities resulting from the abandonment of the salines in the Mondego estuary is significant. Múrias *et al.* (2002) refers that waders present in the estuary uses salines as feeding areas by 42% (over low-tide) to 71% (over high-tide) preferring active than inactive salines. The saliniculture was during long time one of the main economic activities of Figueira da Foz. In the Murraceira was developed for hundreds of years the production of salt necessary not only for drying fish business (especially cod) but also for other industry branches (Duarte, 2008). Nevertheless, diverse constrains led to a marked progressive decline and abandonment of that activity. From 1986, started a conversion of inactive salts-works from the Murraceira Island and margins of the south arm in semi-intensive fish farms of seabass (*Dicentrarchus labrax*) and gilthead seabream (*Sparus aurata*), representing actually an important economic activity in the region (Duarte, 2008; Pinto *et al.*, 2010). From the above evidences, it is easily perceivable the classification of Mondego estuary as an Important Bird Area in 2002 (IBA; PT039) and as a RAMSAR site in 2005 (Ramsar n°. 1617). Either, the Mondego estuary is integrated in the Reserva Agrícola Nacional (National Agricultural Reserve) and Reserva Ecológica Nacional (National Ecological Reserve).

#### 4.4. Impacts on the Mondego Estuary

Some of the publications found reported the processes involved and the consequences of the severe environmental constrains suffered by the system since the early 1990s due to different anthropogenic stresses (e.g. Marques *et al.*, 1993; Múrias *et al.*, 1996; Martins *et al.*, 1997, Pardal *et al.*, 2000). The pressure in the southern channel is lower than in the northern channel but the first one is more vulnerable to environmental problems, due to its low depth, restricted circulation and higher residence time (INAG, 2007). Through the years, several construction and engineering projects have been completed especially in the northern arm like, intense dredging and sand mining aiming to the maintenance and enlargement facilitating ship access to the commercial harbour (Cunha & Dinis, 2002). Those interventions induced the interruption of the upstream communication between the two channels of the estuary from 1991 to 1997 due to sedimentation. Consequently, the river discharge

was mainly through the northern channel and the water circulation in the southern arm became dependent on tides and on the small freshwater input from the Pranto River, artificially controlled by a sluice (Lillebø *et al.*, 2004). The high water residence time, mainly in the south arm, coupled with increased nutrient discharge from the agriculture fields around the estuary led to eutrophication which resulted in algal blooms. As a consequence, profound modifications in the Mondego communities occurred. The result was the disappearance and replacement of *Zostera noltii* (considered a rich habitat in terms of biodiversity and productivity) by opportunistic macroalgae, mainly *Ulva spp.* in the inner most disturbed areas of the estuary (Cardoso *et al.*, 2004). The eutrophication and the consequent estuarine degradation was the subject of diverse papers (e.g. Marques *et al.*, 1993; Múrias *et al.*, 1996; Martins *et al.*, 1997; Lillebø *et al.*, 1999; Cardoso *et al.*, 2002, 2004; Dolbeth *et al.*, 2003) reporting the effects of macroalgae blooms on various species living in the estuary, from seagrasses to waders. One of the main structural modifications was the decrease in species diversity along the eutrophication gradient over time (Cardoso *et al.*, 2004), and an overall secondary production decrease (Dolbeth *et al.*, 2003), with a marked impoverishment of the most disturbed inner area.

Additionally to the eutrophication, during the mitigation measures the system suffered the pressure of natural stressors like floods (1993, 2000/01, 2006), big droughts (2005), and heat waves (2003, 2005) (Dolbeth *et al.*, 2011; Verissimo *et al.*, 2013a).

Beyond the eutrophication, chemical pollution has been also centre of major concern. In recent years some students have been developing their MSc and PhD projects about chemical contamination in the Mondego estuary. Both organic and inorganic pollutants have been addressed. Estrogens, mercury and polychlorinated biphenyls have been quantified in the water, sediments and biota. The current data shows that Mondego estuary could be considered a reference in respect to the mercury (Coelho *et al.* 2005, 2008), animal or pharmaceutical estrogens and alkylphenols (Ribeiro *et al.*, 2009), polychlorinated dibenzo-p-dioxins, polychlorinated dibenzofurans and dioxin-like polychlorinated biphenyls (Nunes *et al.*, 2011), but not for other contaminants like phytoestrogens and bisphenols that were found in high levels in Mondego estuary waters (Ribeiro *et al.*, 2009). The projections suggest an increase of 8% annual growth of urban area and a population growth of 0.16% in the Mondego estuarine zone (Pinto *et al.*, 2011). Consequently, the pollutants and nutrient input originated from the human activities will increase. For that reason, the Mondego estuary deserves continuous monitoring programs on chemical contamination. Additionally, recent studies (Baeta *et al.*, 2009a, b) using stable-isotopes analysis of the community of producers and consumers of the south arm, has shown that the sources of nitrogen are coming from human activities.

Not only anthropogenic drivers have been affecting the estuary but also natural ones like extreme climate events (Marques *et al.*, 2007; Martinho *et al.*, 2007b; Grilo *et al.*, 2011) cited above and invasive species (Franco *et al.*, 2012) have been acting upon the system. Concerning climate change effects in the Mondego estuary, some studies detected drought



induced changes for instance in zooplanktonic assemblages and fish communities (Martinho *et al.*, 2007b, Primo *et al.* 2009). Primo *et al.* (2009) observed that the drought period was associated with an increase in zooplankton abundance, a reduction in the seasonality and a higher abundance and prevalence of marine species throughout the year. Either, Martinho *et al.* (2007b) found a decline in the abundance of the fishes *Pomatoschistus microps* and *Pomatoschistus minutus*. Grilo *et al.* (2009) reported that floods and heat waves had a higher negative effect on macrobenthic assemblages than the droughts.

The water degradation resulting from increasing human-induced pressures is a crucial point of concern for the researchers on Mondego estuary and also for the policy makers. The researchers have been testing evaluation tools for quality status assessment, especially in the implementation of the Water Framework Directive, mainly through the analysis of macrobenthic communities (e.g. Cardoso *et al.*, 2007; Teixeira *et al.*, 2009; Veríssimo *et al.*, 2013a,b) but also through nutrients (Lillebø *et al.*, 2007) and fish communities (Martinho *et al.*, 2008). The results of the evaluation of the estuarine quality status differs not only of the moment of the evaluation and species included but also on the index used, evidencing the high level of mismatch between indices.

#### 4.5. Mitigating measures and responses

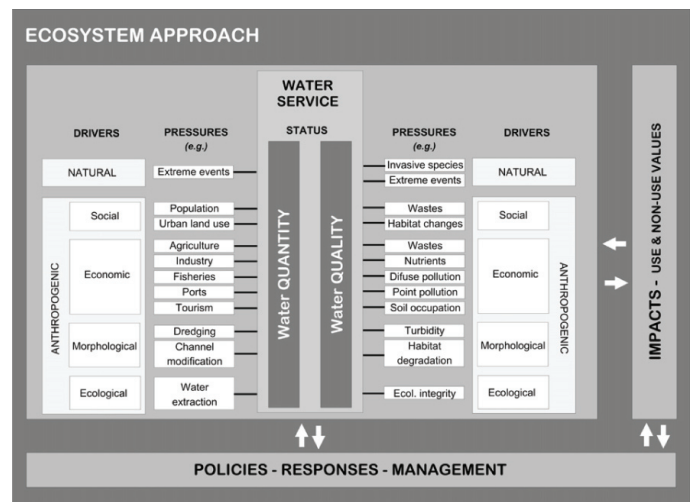
To mitigate the consequences of the diverse impacts on the estuary and prevent further environmental degradation some restoration measures were implemented through the years. The first important measure was started in 1997/98 in the sequence of the estuarine eutrophication. A restoration project was employed in an attempt to improve the ecological status of the system and return it to its original condition. The remediation actions included: the physical protection of the seagrass patches from human disturbance; the change of the discharge location of Pranto River flows and the re-establishment of the connection between the two estuarine arms to improve the hydrodynamic conditions of the south arm and diversion of nutrient rich freshwater inflow (Cardoso *et al.*, 2005, 2008; Duarte *et al.*, 2008). However, the mitigation procedures allowed only a very limited water to flow from the northern into the southern channel at high tide spring tides (Lillebø *et al.*, 2005). The full re-establishment of the communication between both channels was implemented in May 2006. It is important to note that the management programs performed were based in the conclusions of the scientific research held by the Portuguese researchers. Monitoring programs started in 2003 and are going on so far. The data collected are supporting some forecasts of the management measures results (INAG, 2007).

The results from the monitoring program have been an important achieve during the last years, enabling the establishment of some conclusions about the system processes and behaviour. After the various restoration efforts implemented to avoid eutrophication, extensive research have been focused in monitoring its efficiency trying to assess the effectiveness of the recovery actions (e.g. Cardoso *et al.*, 2005, 2007, 2008; Lillebø *et al.*, 2005, 2007; Teixeira *et al.*,

2008; Dolbeth *et al.*, 2011, Falcão *et al.*, 2012; Grilo *et al.*, 2009, 2012; Veríssimo *et al.*, 2012, 2013a, b). The estuarine communities have been showing some signs of recovery (e.g. Cardoso *et al.*, 2008; Grilo *et al.*, 2009, 2012).

During the mitigation measures the system suffered the pressure of natural stressors (previously mentioned above). Those events could have reduced the performance of individuals following the first stressor (eutrophication) and may have contributed to a decline of resilience of the species assemblages to the following stressors (extreme event), thereby slowing or even reversed the recovery process (Cardoso *et al.*, 2008; Dolbeth *et al.*, 2011; Veríssimo *et al.*, 2012, 2013a). In fact, the response of water quality and biological communities to restoration efforts seemed to have been masked by the effects of climatic variability (Falcão *et al.*, 2012; Veríssimo *et al.*, 2012; 2013a).

For all the above mentioned reasons, the Mondego estuary is a challenge to modelling. Through the years, many ecological models have been developed for this estuary aiming to assess the effects of some important periods already mentioned before, e.g. the eutrophication process; the mitigation measures implemented; the centenary flood (winter 2000/01) (e.g. Martins *et al.*, 1997; Patrício *et al.*, 2004, 2006; Silva-Santos *et al.*, 2008; Baeta *et al.*, 2011). Either, a conceptual ecosystems model approach (Fig. 4) was constructed by Pinto *et al.*, (2011) based in the Drivers-Pressures-Status-Impacts-Responses methodology. As referred by the authors, the integral view of the system suggests that there are no linear relationships or direct cause-and-effect patterns among drivers, impacts, and system status, because the interactions among them are complex.



**Figure 4.** Conceptual model of Mondego estuarine ecosystem (from: Pinto *et al.*, 2011).

**Figure 4.** Modelo conceptual do ecossistema estuário do Mondego (retirado de: Pinto *et al.*, 2011).

## 5. CONCLUSIONS

In this study, dealing with Mondego estuary research outputs, some significant points on the research trends were obtained throughout the period from 1989 to 2012. Mondego estuarine research continually grew in the last years. This estuary has long constituted a remarkable field of study, mainly academic. The available literature represents an essential source of information, indispensable for researchers, environmental managers, and decision police makers that will have to deal with this complex system. Considering the need to preserve the Mondego estuary habitats, biodiversity and resources, efforts must continue to better understand the ecosystem functioning, with the intention of carry on integrated management actions. The aim must to provide the means for harmonise human activities with the protection of ecosystem that are fundamental to a sustainable socioeconomic growth and development. In this way, it is essential an effective collaboration between all society members. Moreover, for the production of useful and interdisciplinary information on coastal zones to support the policy decisions, is critically needed to government structures to encourage, facilitate and provide financial support to the continuous investigation.

Finally, besides the Mondego estuary and the research performed so far to be very important for science and for support management decisions, we think that it could be also valuable for didactic purposes. From our point of view this estuary has potential for development of environmental educational projects, and future considerations about this topic will be interesting to follow. The role of research teams should include also the Education for the sustainability.

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