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Towards a DPSIR driven integration of ecological value, water uses and ecosystem services for estuarine systems

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ABSTRACT

The aim of this paper is to indicate the overall economic efficacy of competing uses of estuarine resources by integrating ecological value, water uses and ecosystem services into the DPSIR conceptual framework as an added value for policy making and management. The complex interactions between the socio-economic system and the ecosystem (as part of the 'integral system' as suggested by the second author before) require generic but still 'tailor made' techniques to quantify all relevant variables and to provide an integral view of the system's status. One of the few techniques that can assist in structuring such complex data in an integrative way is the Drivers-Pressures-Status-Impacts-Responses (DPSIR) approach. Support and regulatory services (such as water supply and water quality) are essential to sustain crucial ecosystem processes and functions while the water required for human activities (water demand) is an essential system service. With the help of DPSIR, the main changes in the Mondego Estuary ecosystem (Portugal) were outlined, used as an illustrative example, and causes and effects described. Within the Mondego Estuary region the main water consumers are agriculture, industry, and households. Baseline scenarios predict an increase in water usage by mainly the touristic service sector. Our analysis illustrates that pressures from human population growth and related activities gradually increased over the studied period. Land-use patterns, diversion of freshwater flows, water pollution and morphological interventions directly caused physical, chemical, and biological modification and degradation. This consequently led to negative ecological and socio-economic impacts, such as eutrophication. The scenarios suggest an increased pressure based on an expected 8% annual population growth and an average annual decreased pressure of 5.2% per annum due to the current reduction in agriculture. The results show that understanding the water use-related complex and intricate trade-offs among ecological, social, and economic goals is fundamental in designing and implementing management policies and ecosystems restoration schemes.

1. Introduction

Every ecosystem provides essential services and goods, contributing to the satisfaction of human needs and changes in well-being and delivers irreplaceable support functions on which human life relies (Costanza et al., 1997; Boyd and Banzhaf, 2007). According to the Millennium Ecosystem Assessment (MEA) classification (MEA, 2005) four categories of services can be established: *provisioning* (products obtained directly from the ecosystems); *regulating* (benefits obtained from the regulation of ecosystem processes); *cultural* (nonmaterial benefits people obtain from ecosystems through cognitive development and aesthetic experiences, for example); and *supporting* (benefits necessary for the production of all other ecosystem services). From these, water resources can be considered as a cross-sectoral issue, being found within several of the mentioned categories. For example, the water cycle may be considered within the regulation category (e.g. biochemical cycles that are fundamental to all living organisms and ecosystem functions, such as chemical, element or nutrient (re)-cycling) (Hawkins, 2003), while water supply for human consumption and for economic activities may follow within the provisioning category. Despite their inherent importance, economic values attributed to water resources depend both on consumer preference and on the perception of possible changes in well-being through ecosystem impacts (Turner et al., 2000; Chen et al., 2009). Although the MEA

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framework may be considered as the most widely recognised approach, numerous attempts to develop concepts and classifications have, however, been conducted since 2005 (e.g. Beaumont et al., 2007; Fisher et al., 2009; de Groot et al., 2010; Atkins et al., 2011). Some achievements are, for example, the clear separation among ecosystem processes, functions, services and benefits to societies, creating a sequence from fundamental services (defined by the environment-organisms relationships), via final services (biotic processes ruling the biology–biology and biology–environment interactions), to the societal benefits (benefits of the ecosystem for humans well-being) (Luisetti et al., 2010; Atkins et al., 2011).

Due to typical aspects of coastal areas such as the high population densities and its increasing socio-economic demands, estuarine ecosystems are progressively subjected to anthropogenic exploitation and disturbance. For water, and for the service categories where it is included, one of the direct consequences of anthropogenic presence may be environmental degradation. The ecological status and assessment of water bodies is thus one of the most prominent environmental, social and economic concerns (Marques et al., 2009; Pinto et al., 2010). Therefore, the accurate characterization of the main pressures and impacts from human activities are required for any economic analysis on water uses and services when performing environmental assessments. From an ecological point of view, the Drivers-Pressures-Status-Impacts-Responses framework (hereafter DPSIR) (OECD, 1993) is considered an insightful framework for integrating quantitative and qualitative ecosystem/socio-economic interactions (Turner et al., 2000; Elliott, 2002; Borja et al., 2006; Marques et al., 2009). Hence, this approach allows for the assessment of the link between the ecological characterization of ecosystems (wetland functions) and their economic valuation (uses) in a system. This framework is particularly pertinent when used in parallel with scenarios' development, highlighting the potential impact of current socio-economic developments while assessing current trends in water status (Trombino et al., 2007).

It is widely accepted that estuaries are among the most productive and valuable natural systems around the world (Costanza et al., 1997; Jørgensen, 2010). Due to this, the management of estuarine environmental quality should be focussed on the sustainability of human activities in coastal zones. One possible measure of the coastal system's condition is its capacity to sustain human uses. Decisions that may influence wetland resources should consider the full range of benefits and values provided by wetland ecosystem services (Birol et al., 2006; Trush et al., 2009). The combination of composite or integrative approaches (e.g. DPSIR) with social-ecological system analysis may provide a robust approach for implementing and monitoring mitigation strategies to reduce system degradation (Karageorgis et al., 2005). Therefore, wetlands vulnerability analysis should involve water quantity and environmental quality as well as water supply-and-demand requirements.

Based on the above, the DPSIR framework was used as an integrative tool to combine the qualitative/quantitative ecosystem and socio-economic interactions, while assessing the link between wetlands functions and their uses. This analysis allowed the development of scenarios for the area contributing to implementing mitigation strategies meant to reduce estuarine deterioration, under the Water Framework Directive goal (to achieve Good Ecological Quality Status by 2015) (IMPRESS, 2002). Moreover they serve the improvement of monitoring schemes. The main objective of this study was to demonstrate the overall economic efficacy of competing uses of estuarine resources by integrating ecological values, water uses and ecosystem services into the DPSIR conceptual framework as an added value for policy making and management.

2. Methodology

2.1. The study-site

2.1.1. Mondego Basin: physical characteristics

The Mondego Basin, located in central Portugal, has a catchment area of approximately 6670 km^2, and is highly diverse in topography, hydrology and land use. Its functional structure ranges from mountainous areas to a large alluvial plain discharging into the Atlantic Ocean (Marques et al., 1997; Graça and Coimbra, 1998). The Lower Mondego region (with a total area of 250 km^2) connects the mountain river with the ocean and consists of open valleys and plains. This region also includes the Mondego Estuary (7.2 km^2; Fig. 1). The main focus of this study is the Mondego Estuary as part of the Mondego River basin.

2.1.2. Socio-economic characteristics and interactions

The Mondego River basin provides a high variability in environmental and social conditions. Over half a million people live and work within the Mondego floodplain. The area around the Mondego Estuary is more densely populated (167 inhabitants km^{-2}) than the rest of the basin (circa 90 inhabitants km^{-2}). The area covers a wide range of uses, such as intensive agriculture and industry. Consequently, the water flowing into the estuary has been loaded with nutrients and polluting compounds for already decades. In the Lower Mondego, strong pressures are caused by the primary economic sector (15000 ha of highly productive agriculture of mainly rice) and by harbour-related activities in Figueira da Foz. Secondary and tertiary economic sectors are well represented among the total economic activities of the entire basin. There are a number of relevant existing impacts due to human activities and engineering (Pinto et al., 2010). Engineering activities, such as the Serra da Estrela hydroelectric system (360 GWh annual production) and the occurrence of some dams have changed the hydrological conditions. The latter system was built to prevent the area from flooding and for irrigating the Lower Mondego region (Lima and Lima, 2002).

2.1.3. The Mondego Estuary ecosystem

The Mondego is a warm-temperate shallow and turbid tidal flat estuary with a mean tidal range of 3 m and strong tidal currents. The estuary is divided into two arms by Murraceira Island 7 km upstream from the tidal inlet of the estuary (Fig. 1). The two arms have very distinct physical and chemical characteristics that influence the local ecological conditions. The North arm is relatively deep and constitutes the main navigation channel. The South arm is relatively shallow and is characterised by large intertidal flats during low tide (75% of total area). Land use (mostly fish farming and agricultural areas) has changed the morphology, and consequently the hydraulics and related ecological conditions, of the South arm. Between 1992 and 1998, sediment accumulation at the divergence of the two arms blocked water circulation and changed the southern sub-system almost into a coastal lagoon (Neto et al., 2008), because the fresh river water was mainly discharged via the northern arm. During this period, water circulation in the southern arm was mostly driven by the tides and the freshwater input from the Pranto River tributary of which the discharge is strongly influenced by water extraction for rice agriculture (Flindt et al., 1997; Marques et al., 2003). This freshwater input into the system created an a-typical water regime while at the same time serving as an important nutrient source to the system. The result was blooms of green macroalgae (Martins et al., 2001, 2007; Patrício et al., 2007) and a concomitant decrease of *Zostera noltii* meadows (previously described as a highly productive system) (Marques et al., 1997; Patrício et al., 2004). From 1998 onwards,

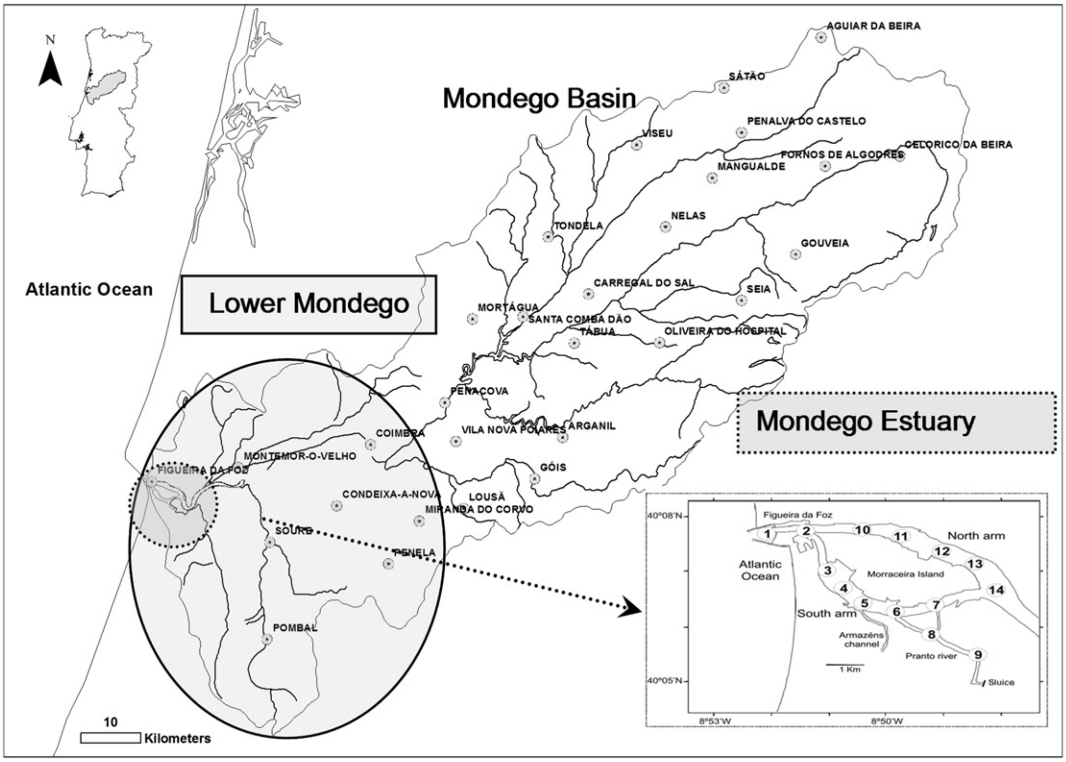

Fig. 1. Study-site location and the three considered scales: Mondego Estuary, Lower Mondego, and Mondego Basin.

experimental mitigation measures were implemented (Neto et al., 2008; Lillebø et al., 2007; Patrício et al., 2009): 1) the seagrass meadows were protected from human physical disturbance; 2) there was a reduction of nutrient loadings into the South arm (e.g. mean N/P changed from 39.8 to 13.2; diversion of the nutrient-enriched freshwater to the North arm by another sluice located more upstream); 3) public awareness programs on the importance of intertidal seagrass to ecosystem health and economic activities were implemented; and 4) improvement of the hydraulic regime by enlarging the connection between the two arms (reduction of water residence time in the South arm from 9 to 6 days, using the methodology described in Braunschweig et al., 2003). The performed hydro-morphological changes reduced the probability of eutrophication symptoms and other problems associated with water pollution in the South arm.

Based on the estuarine salinity gradient and subtidal soft-bottom habitat characteristics, the Mondego's lower estuary can be divided into four ecological areas (Fig. 1): euhaline estuarine sand (stations 1, 2, and 10), North arm polyhaline sand (stations 11 to 14), South arm polyhaline sand (stations 3 and 4), and South arm polyhaline muddy sand (stations 5 to 9) (Teixeira et al., 2008).

2.2. *Adopted framework*

The DPSIR framework was used as an analytical tool to trace changes in the transitional wetlands structure and function over time in relation to human uses. The main driving forces were identified and their impacts on the system functioning evaluated (Fig. 2). At this stage, also the scale issue was considered by drivers- and pressures trend analysis carried out at successively higher geographic scales: Mondego Estuary, Lower Mondego, and Mondego Basin (Fig. 1). This approach was used to assess water condition and status in the most seaward part of the Mondego River and to make inferences about the effects of upstream activities on the estuarine region. Due to data availability constrains the 1994 (initial condition)-2006/07 (final condition) time period was selected for the socio-economic quantification, and the years 1990–2006 for natural drivers and ecosystem status evaluation.

2.2.1. *Inventory and description of drivers*

Identified drivers were divided into two broad categories (IMPRESS, 2002): 'natural' (which can be assessed, but not controlled), and 'anthropogenic' (human driven changes that can be assessed and controlled) (Fig. 2).

a) Natural drivers

Included in this category were species invasions that occurred in the study area and that may have interfered with the system integrity, and extreme events occurring on the system. The assessment on exotic species was mainly based on existing secondary data (e.g. Anastácio and Marques, 1996). For the period 1990–2006, extreme events (like dry years) were defined based on mean annual and mean summer temperatures (°C) and based on the total annual precipitation (mm). The required data were obtained from national institutes as INAG (Water Institute; www.snirh.pt) and IM (Meteorology Institute; www.meteo.pt).

b) Anthropogenic drivers

The anthropogenic drivers were divided into four sub-classes: social, economic, morphological, and ecological.

The social drivers were evaluated by population factors (total number, population density, and household numbers) and urban land occupation rates. These can be used as a useful proxy for the use of freshwater. To do this, human use-related relative changes (expressed in percentages) were weighted against the changes in percentages of the same factor but at other spatial scales (Mondego

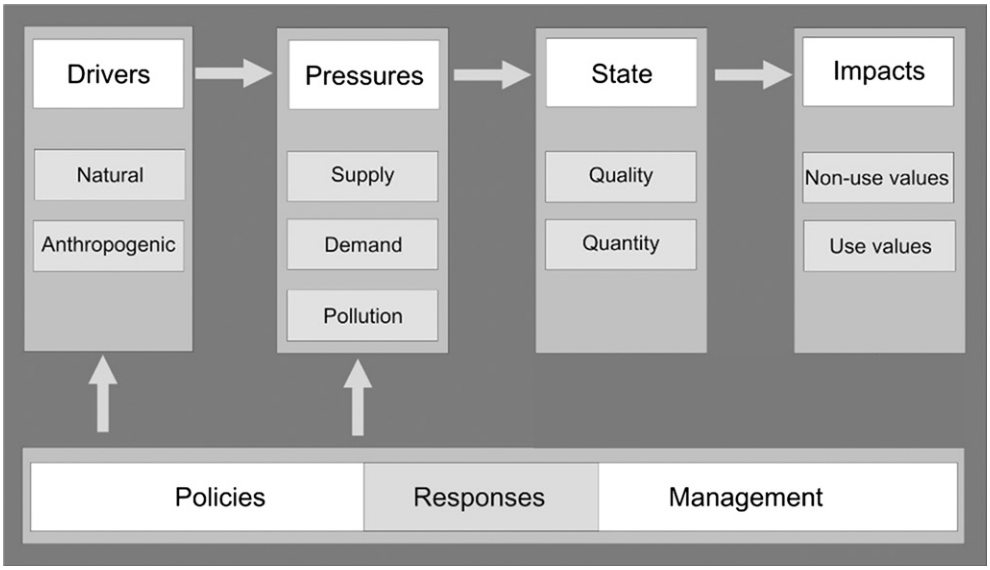

Fig. 2. DPSIR approach applied for the Mondego Estuary: identification of (natural and anthropogenic) Drivers, and of the main Pressures occurring on the supply, demand and pollution of aquatic resources. This allowed for a qualitative and quantitative Status evaluation, and for measuring the Impacts on the use and non-use values of the system. The societal Responses meant to improve the system should take into account both implemented policies and management actions taken (past and future).

Estuary, Lower Mondego, and Mondego Basin). The data were then compared with the multi-scaled GDP (Gross Domestic Product) per capita, which can be used as a rough indicator for the standard of living and can be calculated at multiple spatial scales. Other important social drivers that determine ecosystem orientation are the policies and institutional directives implemented by administrative organizations responsible for managing the system. Within this category, several scales can be considered: the local level (PDM, 'Plano Director Municipal'), where municipal institutions drive system characteristics by engaging local development and growth; the regional level; the national level; and finally, the European Union level.

Six main activities were considered in the economic drivers' assessment: agriculture, fisheries, salt production, industry, the commercial harbour, and tourism. Three main parameters were assessed for each activity: 1) the number of production units (total enterprises dedicated to goods production); 2) the output (total production and/or profits); and 3) employment.

Dredging activities to maintain the fairway (total annual volume) and main physical barriers were considered to be morphological drivers.

Among the ecological drivers, we have estimated total water extraction and the quantity of effluents produced, drained and treated, over the years.

The information for these sub-classes was obtained from national institutions such as INE (National Statistics Institute, www.ine.pt), IPTM ('Instituto Portuário e Transporte Marítimo'), and IPIMAR (National Institute of Biological Resources), consolidated in Pinto et al. (2010).

2.2.2. Evaluation of environmental pressures

A pressure is defined as the direct and quantifiable effect of a driver to the system (e.g. an effect that causes a change in flow or a change in water chemistry) (IMPRESS, 2002). There are several classes of pressures: pressures source type (point and diffuse source pollution), water extraction/regulation, biological resources, hydro-morphological alterations and other anthropogenic impacts (e.g. port maintenance), and land-use patterns (the percentage area dedicated to/in use by each main activity) (IMPRESS, 2002; Borja et al., 2006). These pressures, alone or in combination, may cause (future) perturbations to the system, potentially leading to the failure of meeting the environmental objectives established by the WFD (Good Ecological Quality Status by 2015) (IMPRESS, 2002). The identified pressures for the Mondego system were allocated to 3 main classes (Fig. 2) to facilitate the identification of the components that need to be managed for meeting 'sustainable use' of the natural resources: 1) Pressures on water supply (including a water services inventory); 2) Pressures on water demand (including a water uses assessment); and 3) Pressures on water quality. Also the defined main indicators were related to each activity to quantify the several pressures.

We evaluated several items and related socio-economic factors to the environmental assessment. A crucial distinction had to be made between water services and water uses. According to IMPRESS (2002), water services are intermediate between the natural environment and the water use. Stakeholders are an important component in the valuation process and must be considered. Their preferences for how water should be managed determine the planning and decision process. Therefore, two inventories were performed: 1) water services (all services of extraction, storage, treatment and distribution of surface water or groundwater, including wastewater collection and treatment facilities) and 2) water uses (divided into industrial, agricultural and household). To infer the importance of water to the local human population and to the ecological maintenance, a supply and demand rate analysis of water uses was performed for the main consumers: domestic, agricultural, industry, and tourism. The analysis of agricultural use was based on irrigation for the basin (101 395 ha) and on the irrigation facility constructed to improve water efficiency in the Lower Mondego ('Aproveitamento Hidroagrícola do Baixo Mondego', or AHBM). The general data used for this section were obtained from INE (www.ine.pt), while the data on quantitative water extraction and its use for agricultural irrigation were obtained from INSAAR (http://insaar.inag.pt).

2.2.3. Ecosystem status assessment

Regarding the status of the system, two components were considered: the quality and quantity of water resources (Fig. 2):

a) Water quality

In 1990, 1992, 1998 and from 2002 to 2006 sampling was carried out at 14 stations along the seaward part of the estuary which includes all ecological areas (Fig. 1). The sampling areas were assumed to deliver information on two general indicators: water quality and ecological state. Water quality was analysed based on spring concentrations of dissolved nutrients (nitrate, nitrite and phosphorus, in μmol l^{-1}). Quantifications were made from surface and bottom-water samples in the main channels. Water nitrate (NO_3) and nitrite (NO_2) concentrations were analysed according to standard methods described in Strickland and Parsons (1972). Ammonium (NH_4) and phosphate (PO_4) concentrations were analysed following the Limnologisk Metodik (1992). Nutrient sources were determined following EEA guidelines ('European Environmental Agency') (EEA, 1999) prepared by the European Topic Centre on Inland Waters (ETC/IW). The subtidal soft-bottom benthic macroinvertebrate community was used as a proxy for the ecological status of the entire ecosystem. The focus relied on the community's responses to pressures on the environment. Benthic communities were chosen as indicators because biological communities are a product of their environment, and also because different benthic organisms have demonstrated to have different habitat preferences and pollution tolerance levels (Pinto et al., 2009). On top of that, the response of the biological communities of the Mondego Estuary to environmental stress have been studied for the past 25 years (Marques et al., 1997; Patrício et al., 2009), allowing inferences to be made on long-term responses to environmental change. The ecological status of the system was assessed using an integrative environmental index (BAT, Benthic Assessment Tool) already applied to the Mondego Estuary before (Teixeira et al., 2008, 2009). To evaluate the status of the ecosystem the BAT integrates three widely used but different metrics, 1) the Shannon–Wiener Index (H′) (Shannon and Weaver, 1963), 2) the Margalef Index (d) (Margalef, 1968), and 3) the AMBI (Marine Biotic Index) (Borja et al., 2000). Following the WFD requirements (EC, 2000), the overall index values range from 0 (bad ecological quality) to 1 (high ecological quality). The ecological meaning of the values was subsequently expressed in one of 5 defined quality classes (Bad, Poor, Moderate, Good, and High).

b) Water quantity

Water quantity analysis focused mainly on the available aquatic resources *versus* their usage in the system over the years (water supply/demand relation). To undertake this analysis secondary data obtained from INE and INAG institutions (e.g. water volumes consumed by economic or domestic activities) were used.

2.2.4. Assessment of impacts

The effects that 'direct' and 'indirect changes' of the ecosystem status may have on human well-being were also considered. The system wide total economic value used includes two main value classes: the use and non-use values. The use values class represents the direct use values, derived from both extractive and non-extractive human activities within the ecosystem (e.g. fisheries); the indirect use values, represented by services provided by the system (e.g. recreation); and the option values, where humans maintain the option to use the system in the future. Finally, the non-use values are associated with the inherent value of the system (e.g. bequest value) (Table 1). As so, two main categories were considered (Fig. 2):

a) Impacts upon use values

Two main parameters were considered for the valuation of water use values: the taxes (benefits) paid by some sectors, and the costs of treating water resources. These measures provide an

Table 1
Impacts assessment: Water resources total economic value (TEV): water use (direct, indirect and option) values, and non-use values (existence values) of different services/resources (adapted from Atkins et al., 2007); and most used valuation methods to determine water resources values (adapted from Young, 2005).

Values			Services/Resources	Method for valuation
Total Economic Value (TEV)	Water Use values	Direct Use value	Recreation	TC; BT
			Commercial fishing	MP[a]; PF
			Agriculture	MP; PF
			Households	MP[a]; DC; CM
			Industry	MP[a]; PF
			Salt-works	MP; PF; TC
			Urban supply	MP
			Drinking purposes	MP; DC
			Biodiversity uses	MP; RRC; BT
			Energy production (e.g. wind, wave, tidal, and thermal power)	MP; CM
			Wastewater assimilation	DC; MP[a]; BT
			Research/Education	CVM; BT
			Tourism/Ecotourism	TC[a]; DC; BT
		Indirect Use value	Aesthetic value	TC; DC; BT
			Recreational fishing	TC; CVM; DC; BT
			Human health	DC; BT
			Tourism/Ecotourism	TC; CVM; DC; BT
			Recreation	TC; CVM; DC; BT
			Biodiversity assets	CVM; RRC; BT
			Wastewater assimilation	DC; RRC; BT
			Landscape maintenance	CVM; BT
			Research/Education	CVM; BT
		Option value	Future uses as per direct and indirect use values	DC; CVM; RRC, BT
	Water Non-Use values	Existence value	Estuarine zone as an object of intrinsic value, as a gift to others, and as a responsibility (stewardship)	HP; TC; CVM; RRC; BT

Note: MP: market prices method; PF: productivity function; BT: benefit transfer; TC: travel cost; RRC: replacement and restoration costs; HP: hedonic pricing; CVM: contingent valuation method; DC: damage costs; CM: choice modelling.
[a] Used in this study.

overall estimation of the values that the local population pays for water services. Following Henriques and West (2000), the following parameters were taken into account in evaluating the costs and benefits of water resources: the benefits obtained (e.g. market price values) and the cost values (e.g. residual water taxes implemented). Environmental costs indicate the damage that water use imposes (e.g. reduction in the ecological quality of aquatic ecosystems) (WATECO, 2003). Likewise, resource costs represent foregone opportunities, which other uses suffer due to the depletion of the resource beyond its natural rate of recharge or recovery. Data on the investments, costs, and income of water supply and wastewater drainage and treatment were obtained from INE and were used as a proxy to estimate the water (financial) costs for 2006. To evaluate the urban water supply and its environmental costs, the figures of the investments in wastewater treatment service were used. The benefits were measured as infrastructure taxes (that internalise the indirect benefits of hydraulic infrastructure) and water extraction taxes (that provide price discrimination through net benefits for users, water availability, and user efficiency) (Henriques and West, 2000). These benefits were calculated by (Henriques and West, 2000)

$$T = A \times K_1$$

where T is the tax value; A is the water volume extracted (m^3); and K_1 is the final value of the water extraction per m^3.

Overall costs were calculated with residual water taxes (that claim to calculate the marginal cost of pollutant reduction and the adequate treatment level in wastewater treatment plants). This is given by (Henriques and West, 2000)

$$T = \sum_{i=1}^{n} p_i \times K_{4i}$$

where T is the tax price; p_i the annual rejected water volume because of any pollutant i; and K_{4i} the treatment cost.

b) Impacts upon non-use values (environmental integrity)

Focussing on water quality impacts evaluation, the main processes and their effects (direct or indirect) on the system status and on human well-being were qualitatively analysed. Using a continuous water quality/quantity analysis, a Spearman correlation was performed to test the relationship between main criteria selected from the estuarine DPSIR approach (e.g. tourism data or urban occupation) and the nutrient concentrations in the water column.

2.2.5. Socio-economic responses

A 'response' by society or policymakers is the result of an undesired impact and can affect any part of the chain between drivers and impacts (Turner et al., 2000). Two main factors were considered (Fig. 2):

a) Policies and directives

An assessment was performed of the main actions applied to the system in the past and the simulated system responses to the occurring environmental alterations. These results were transposed to the current problems in the system. Due to its mandatory nature, special attention was given to the WFD. Under the goal of achieving a good ecological status by 2015, the WFD demands the assessment of future trends in environmental conditions that should be performed by developing baseline scenarios which examine the consequences of current trends in population, economy, technology and human behaviour (EC, 2000; Trombino et al., 2007). Data from 2006 were chosen for baseline scenario development, due to its wide-ranging availability (covering all required fields). The baseline scenario analysis was conducted using the average difference between the main drivers and pressures in 1994 and in 2006, assuming that these ratios would not change until 2015.

b) Management actions

A conceptual overview of the main water services and uses, as well as their major trends over time, was set up to establish baseline scenarios for economic analysis. This approach allowed a full integration of ecological potential, natural variability and functioning while providing a comprehensive analysis of the water system and its importance to the local population. The ultimate aims were to contribute to knowledge of the system's resilience and to make inferences for management-related issues that were or could be implemented on the system.

3. Results

3.1. Inventory and description of drivers

Table 2 shows the main considered drivers acting upon the system and the selected indicators used to quantify the pressures acting on the estuarine resources. The quantification of changes occurring on the system was given by the difference between the indicator value for the initial condition (1994 year) and for the final year (2006/07), allowing the calculation of the relative difference in the indicator value over the 14 years' timeframe.

a) Natural drivers

Within this category we have included invasive species that have caused substantial hazards in the system (Table 2). At the basin scale, the silver wattle (*Acacia dealbata*) threatens natural riparian vegetative communities (Costa et al., 2001). At the Lower Mondego scale, more specifically at the rice-fields, the crayfish *Procambarus clarkii* was accidentally introduced in the early 1990s and severely damaged drainage systems and rice crops by their digging (Anastácio and Marques, 1996). The introduced mosquitofish (*Gambusia holbrooki)* feeds on eggs of economically desirable fishes, as well as on rare indigenous species (Mieiro et al., 2001). In the Lower Mondego and upstream areas, the introduced Asian clam (*Corbicula fluminea*) has a dispersion potential that may lead to changes in food webs, biofouling problems and competition with local species (Sousa et al., 2007; Miehls et al., 2009). The other natural driver considered were the extreme events occurring on the system (Table 2). Mean annual temperatures varied between 14.4 and 16.6 °C, while mean summer temperatures ranged from 14.6 to 17.8 °C, the warmer years being 1998, 2003 and 2005 (Fig. 3, dark-Gy bar), along with low annual precipitations (characteristic for drought years). 1995, 1997 and 2000 were flood years with annual precipitations that ranged from 1122 to 1378 mm (Fig. 3, light-Gy bar).

b) Anthropogenic drivers

Within the anthropogenic drivers, the following four subcategories were analysed:

A. Social drivers

There was an increase (2.3%) in the number of residents in the Mondego Estuary between 1994 and 2007 (Table 2). Although the Lower Mondego region growth rate was twofold that of the other

Table 2
Main drivers, selected indicators, dissimilitude values and %/year between 1994 and 2007, for the different spatial scales (MB- Mondego Basin; CR- Central Region; LM- Lower Mondego; ME- Mondego Estuary).

	Drivers	Selected indicator	Region	Years		Dissimilitude (%)	%/year
Natural	Natural						
	Invasive species		MB, LM, ME				
	Extreme events						
	Floods	Precipitation (mm)	ME				
	Drought	Annual temperatures (°C)	ME				
Anthropogenic	Social						
	Population			1994	2007		
		Total population (n°)	MB	846 000	879 570	4.0	0.28
			LM	327 770	332 355	1.4	0.10
			ME	61 830	63 229	2.3	0.16
		Population density (hab/km^2)	MB	88.1	90.3	2.5	0.18
			LM	158.9	161.1	1.4	0.10
			ME	163.0	166.8	2.4	0.17
		Households number (n°)	MB	373 796[a]	394 549	5.6	0.40
			LM	115 206[a]	122 743	6.5	0.46
			ME	22 976[a]	24 548	6.8	0.48
				2002	2005		
		GDP per capita	MB	62.1	67.5	8.7	2.18
			LM	100.3	103.4	3.1	0.78
			ME	95.2	99.3	4.3	1.10
	Policies and institutional directives	Taxes and incentives					
		Municipal and oriented directives					
		Market trends					
	Economic						
				1999	2007		
	Agriculture	Employment (n°)	CR	330 955	114 528	−65.4	−7.27
		Explorations (n°)	CR	128 119	96 253	−24.9	−2.77
		Output (t)	CR	925 227	875 781	−5.3	−0.59
				1994	2007		
	Fisheries	Employment (n°)	ME	737	560	−24.0	−1.7
		Fishing boats (n°)	ME	319	211	−33.9	−2.4
		Output (t)	ME	12 071	11 008	−8.8	−0.6
				1998	2006		
	Salt-works	Area (ha)	ME	137	33	−75.9	−8.4
		Units (n°)	ME	83	15	−81.9	−9.1
		Production (t/year)	ME	1511	870	−42.4	−4.7
				1998	2006		
	Industry	Enterprises (n°)	MB	94 630	87 472	−7.6	−0.84
			LM	38 158	38 282	0.3	0.03
			ME	7625	6714	−11.9	−1.32
		Employment (n°)	MB	128 472	236 645	84.2	9.36
			LM	53 391	95 695	79.2	8.8
			ME	11 500	19 895	73.0	8.1
		Output (1000 €)	MB	9 038 000	1 620 9328	79.3	8.8
			LM	4 166 000	6 530 833	56.8	6.3
			ME	1 029 000	2 041 247	98.4	10.9
				2003	2007		
	Commercial harbour	Traffic (entrance n°)[b]	ME	269	363	34.9	7.0
				1998	2007		
	Tourism	Lodging capacity (n°)	MB	10 485	11 325	8.0	0.8
			LM	5426	3199	−41.0	−4.1
			ME	2339	1499	−35.9	−3.6
		Output (1000 €)	MB	22 052	36 341	64.8	6.5
			LM	11 704	21 427	83.1	8.3
			ME	3271	6849	109.4	10.9
	Morphological						
	Channel modification	Dredging volumes	ME	1 × 106 m^3 yr^{-1}			
	Physical barriers	Dams	LM				
		Capacity/location					
	Ecological						
				1998	2006		
	Water extraction	Water volume (Hm^3)	MB	59 207	64 353	8.7	1.0
			LM	30 894	32 905	6.5	0.7
			ME	4910	4877	−0.7	−0.1
	Wastewater	Drainage (Hm^3)	MB	23 371	31 219	33.6	3.7
			LM	10 508	15 880	51.1	5.7
			ME	1586	2620	65.2	7.2
		Treated (Hm^3)	MB	18 573	19 539	5.2	0.6
			LM	8146	6084	−25.3	−2.8
			ME	0.539	2474	359.0	39.9

[a] 2001 data.
[b] IPTM data (http://www.imarpor.pt).

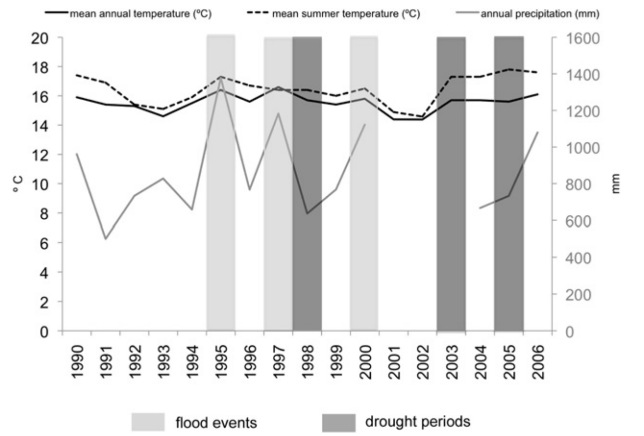

Fig. 3. Mean (annual and summer) temperatures (°C), and Mean annual precipitation (mm). The light-gray bar represent years with flood events; the dark-gray bar represent years with drought periods.

regions, it still was half of the Basins' growth rate. Population density and household drivers (2.4% and 6.8%, respectively) showed the same pattern. These rates were below average across all scales assessed. Nonetheless, GDP (Gross Domestic Product) at the basin level was higher (8.7%) than at the other scales. Several actions have been implemented for local economic and social development. These implementations may have influenced the ecology of the ecosystem. Specifically, these were 1) reinforcement of the urban system; 2) diversification of tourism, with emphasis on ecotourism, and 3) reorganisation of rural areas.

B. Economic drivers

There was a reduction in the total number of explorations in all activities (by number of enterprises, number of explorations, lodging capacity, fishing boats and port entrances). This reduction was concomitant a reduction of the total economic production in primary sector activities. Nevertheless, the total output (by profits and employment rates) of the secondary and tertiary sectors appeared highly profitable (Table 2).

C. Morphological drivers

Through the years, several construction or engineering projects have been completed, such as the creation of artificial river banks, to mitigate the effect of floods, especially in the northern arm. Recurrent dredging and sand mining increase and maintain the channel depth (8–9 m depth below Chart Datum) to facilitate ship access to the commercial harbour (Cunha and Dinis, 2002), especially during winter when strong sedimentation may occur (1–4 cm year^{-1}) (Rocha and Freitas, 1998).

D. Ecological drivers

Water extraction and wastewater management were also considered. Although total wastewater drainage has increased over the years (Table 2) there was a slight decrease in water extraction.

3.2. Evaluation of environmental pressures

In order to evaluate the environmental pressures occurring on the Mondego Estuary, we have attempted to provide an explicit link between driving forces and pressures (measured through specific indicators such as nutrient concentrations or effluents produced) on the supply, demand and quality of water resources (Fig. 2). Each of these pressures may have a positive or negative effect on the water resources condition, which consequently is going to determine the water status (either concerning quality or quantity).

3.2.1. Pressures on water supply

The Mondego Basin has highly diversified water services that are extremely important to the economic development of the region, such as water supply to households and urban systems or agricultural irrigation in the Lower Mondego region. In addition to this direct consumption, a wide range of services and goods depends, either directly (e.g. recreational activities) or indirectly (e.g. maintenance of biodiversity), on the aquatic system quality. The total annual rate of water extraction has increased from 1998 to 2006 in the Lower Mondego (30 894 to 32 905 Hm^3), while there was a slight decrease in the Mondego Estuary (4910 to 4877 Hm^3) (Table 2). Most of the water supply at the Lower Mondego region comes from surface sources, although there was a slight reduction from the surface sources contribution in 2006 (1998: 91.3%; 2006: 74.8%). This may have been a consequence of the AHBM water management project for efficient use of water resources. Moreover, in the Mondego Estuary, most of the water comes from underground sources (1998 and 2006: 60.7%) (INE data).

3.2.2. Pressures on water demand

In the Mondego system the main water users (in terms of total water volume) are population, agriculture, industry, and tourism. Table 3 presents the water demand estimations by the main water consumers of this region. Agricultural fields, by far the biggest demanders on water, are divided between rice (45%), corn (51%), and other crops (4%) together covering 12 546 ha (Costa et al., 2001). The agricultural sector has a number of potential impacts on water quality, not only as a water extractor, but also as a source of diffuse pollution (mainly nitrogen and phosphorous compounds, and pesticides). Per capita the household water consumption is one of the main drivers in the Mondego region (Mondego Basin: 42 m^3; Lower Mondego: 65 m^3; Mondego Estuary: 57.5 m^3) (INE data). With a population of 63 372 in 2006, the Mondego Estuary has a total household consumption of 3643 Hm^3 (corresponding to 16.7% of the Lower Mondego water consumption and 9.8% of that of the Mondego Basin). Growth in households has increased over the study years and is expected to further increase the domestic demand for water. Around 97% of the Mondego Estuary population is served by municipal water supplies and roughly 87% benefit from drainage and treatment wastewater facilities (2006 data, INE data source). These values are higher than regional numbers (98%; 78%). Most households are connected to the main sewage systems ('Inventário Nacional de Sistemas de Abastecimento de Água e de Águas Residuais'-INSAAR data). Wastewaters suffer several treatments along the several considered scales (Table 4A).

3.2.3. Pressures on water quality

A full inventory of pressures on the system was performed. This was based on official reports and local knowledge of system functioning, relating the 5 identified source types with pressures on water resources (demand, supply, and quality). Change in land cover or land use, through land reclamation and use intensification, directly impacted water quality. These activities include land alterations to accommodate households, industries or infrastructures. The main consequences of these land modifications are soil sealing, decreasing soil permeability, and consequently higher peak runoff levels. The opposite effect (less pressure on water resources) is caused by the salt pans areas. This activity, due to its traditional way of salt-extraction, represents a 'less negative' pressure on the system. Despite this activity represents a direct human action and

Table 3
Water and wastewater prices, in 2006, by sector (Domestic, Agriculture, Industrial/Commercial/Tourism and Others): A. Water consumption and wastewater treatment prices for the different spatial scales (Mondego Basin, Lower Mondego and Mondego Estuary) (€/1000 m^3) (source: AHBM-'Aproveitamento Hidroagrícola do Baixo Mondego'); B. Investments, costs and income of water supply (Hm^3) and wastewater treatment services (1000 €) by management operators, in Lower Mondego (INE data).

A. Consumption and wastewater treatment prices

Water consumption

	Sector	Mean supply tariff (€)	Mean water prices (€)	Water volume used (Hm^3)	Mean water extraction prices (€/Hm^3)
Mondego Basin	Domestic	146.40	0.615985	43 264	26 796
	Agriculture total	–	–	466 213	–
	Agriculture AHBM	–	–	–	–
	Industrial/Commercial/Tourism	167.34	1.2296	47 740	587 179
	Others	125.52	0.6104	0.113	194
Lower Mondego	Domestic	146.40	0.615985	19 742	12 307
	Agriculture total	–	–	241 233	–
	Agriculture AHBM	–	–	212 250	–
	Industrial/Commercial/Tourism	167.34	1.2296	36 377	447 459
	Others	125.52	0.6104	–	–
Mondego Estuary	Domestic	146.40	0.615985	4677	3028
	Agriculture total	–	–	43 310	–
	Agriculture AHBM	–	–	26 481	–
	Industrial/Commercial/Tourism	167.34	1.2296	35 763	439 910
	Others	125.52	0.6104	–	–

Wastewater treatment

Spatial scale	Mean wastewater supply tariff[a] (€)	Wastewater volume discharged (Hm^3)	Mean wastewater services prices (€/Hm^3)
Mondego Basin	6.14	499 423	3 068 625
Lower Mondego	6.14	227 857	1 400 031
Mondego Estuary	6.14	47 732	293 282

B. Investments, costs and income of water supply and wastewater treatment services (1000 €)

	Investments (1000 €)	Costs (1000 €)			Revenue (1000 €)		
		Total	General	Management & exploration	Total	Tariff	Other
Water supply							
Lower Mondego	12 651	18 741	3869	14 872	24 234	22 578	1657
Drainage and wastewater treatment service							
Lower Mondego	21 822	13 963	2390	11 573	8582	6942	1640

Note: – no data available.
[a] Mean national values.

occupation of natural ecosystems, it is less invasive for the system quality than most of the other activities present on the system, and so may provide a positive signal on biodiversity and water quality. Along with these factors there are also the natural characteristics of the system. Recorded sedimentation in the estuarine area has influenced the estuarine water circulation and has increased the water residence time (Marques et al., 2003). Although the level of water extraction has not changed over the years, wastewater drainage and treatment volumes have experienced substantial increases. Based on an approximately constant pattern of effluent emissions, wastewater treatment and population behaviour, the wastewater discharges into the (hydrologic) estuarine system were

Table 4
A. Volumes of treated wastewater effluents (m^3), treatment type (total, primary, secondary, tertiary, and unspecified) and treatment points, in 2006 (INSAAR based data); and B. Mean effluents types and discharges (cumulative values among spatial scales; tons $year^{-1}$): Biochemical Oxygen Demand (BOD); Chemical Oxygen Demand (COD); Total Suspended Solids (TSS) at the different spatial scales (Mondego Basin, Lower Mondego and Mondego Estuary).

A. Effluents treatment types, volumes treated (m^3) and treatment points

Treatment type	Basin			Lower			Estuary	
	Volume	%	Treatment points	Volume	%	Treatment points	Volume	Treatment points
Total	15312102	–	676	5130214	–	74	2276908	8
Primary	3952632	25.8	573	429575	8.4	26	–	–
Secondary	4104338	26.8	68	1139900	22.2	16	–	–
Tertiary	506964	3.3	6	92141	1.8	4	–	–
Unspecified	678169	4.4	120	3468598	67.8	28	2276908	8

B. Mean effluents types and discharges ($tons.year^{-1}$)

	BOD			COD			TSS			Nitrate + Nitrite			Phosphates		
	Basin	Lower	Estuary	Basin	Lower	Estuary	Basin	Lower	Estuary	Basin	Lower	Estuary	Basin	Lower	Estuary
Domestic	15 235	6347	1439	34 279	14 281	3238	22 852	9521	2159	2031	846	192	381	158	36
Industry	10 537	9054	8107	29 529	26 635	24 761	5675	4188	3550	–	–	–	–	–	–
Others point sources	1399	0.4	0.4	3443	1	0.9	3000	1.3	0.7	209	0.1	0.1	70	0.0	0.0
Diffuse pollution	–	–	–	–	–	–	–	–	–	2254	85	2.4	158	5.9	0.2
Total	27 171	15 401	9547	67 251	40 917	28 000	31 527	13 710	5710	4494	931	194	609	164	36

Note: – no data available.

estimated (Table 4B; after Costa et al., 2001). The high contribution of domestic and urban effluents to water pollution is reflected by BOD (Biochemical Oxygen Demand), COD (Chemical Oxygen Demand), and nutrient inputs (dissolved nitrogen and phosphorous compounds). Industrial effluents strongly impact the water quality of the Lower Mondego and the Mondego Estuary (Table 4B). From data on total wastewater and treated volumes at different scales, it was verified that most effluents undergo secondary treatment. It was, however, not possible to reliably estimate discharges of all compounds at the scale of the Mondego Estuary.

3.3. Assessing the ecosystem status

a) Water quality

Two parameters were used to assess the status of the Mondego Estuary: 1) the water nutrient condition, and 2) the ecological quality. During almost the entire year, the estuary presented water stratification. Surface waters had consistently higher levels of NO_3+NO_2 and lower quality (worse classifications) than bottom waters (Table 5), suggesting that the main nutrient sources lie upstream the Mondego Estuary terminus. The South arm, a polyhaline muddy sand area, also had worse classifications for NO_3+NO_2 and PO_4 than the North arm. In this southern inland area, the water residence time was longer and agricultural runoff pressure was stronger than in the North arm. Runoff was extremely variable in the Mondego Basin, both intra-annually (winter months with high runoff) and inter-annually (e.g. 2000, a flood year, or 2005, a dry year, INAG data). Mean annual rainfall was 1136 mm, with 720 mm going to evaporation and approximately 400 mm to runoff. Stations with higher water circulation generally had higher quality classifications, which allowed us to infer dilution and runoff capacities. Years with higher precipitation (Fig. 3) showed lower water quality (Table 5), reflecting higher levels of pollutant runoff. In general, we observed poor classifications from 1992 to 2002, which then improved in the period 2003 to 2005 and worsening in the spring of 2006. Episodes of contamination (e.g. 2006) by paralytic shellfish poisoning have been caused by harmful algal blooms, which then led to stopping the shellfish fishery in the Mondego Estuary (IPIMAR data).

Regarding the ecological conditions of the system in 1992, the ecological quality of the North arm strongly declined (Table 5). The ecological quality of the South arm declined until 1998. After 1998, following several experimental mitigation measures, the ecological quality status of the entire system began to show signs of improvement. On the whole, a gradual enhancement of the system has taken place (Teixeira et al., 2009).

b) Water quantity

The comparison between water usage (Table 3) and water availability (e.g. runoff parameters) enables to demonstrate that the actual volume of water provided by the river basin was sufficient to cover all the regional needs. These observations allowed for a dependency estimation that water quality and quantity have on the several pressures occurring on the system. It is indeed possible to demonstrate that factors such as floods and dry conditions may cause a high dependence on both water quality and quantity, while other factors (e.g. urban discharges) may have an opposite effect on both assets (e.g. high for quality and low for quantity).

3.4. Impacts assessment

3.4.1. Impacts upon use values (direct and indirect use values)

At all scales, economic sectors were the main water consumers (Table 3A). The current average selling price is approximately 1.23 €/m^3 for the domestic and industrial sectors (Table 3A), representing an average increase of 3.6% from 1999 to 2006. The total income of water supply activities exceeds the costs of extracting it (Table 3B). The quantification of the benefits related to irrigation constructions for agricultural use, was based on available irrigation networks, like the one in the Lower Mondego region (AHBM). This hydraulic structure has a maximum storage capacity of 500 Hm^3 and supplies water for several purposes (40% industry; 52% agricultural irrigation; 8% public consumption). It was built for a total of 675 000 € (1997 prices) (Costa et al., 2001).

When only the financial costs and revenues achieved from drainage and wastewater treatment are considered then the costs by far outweigh the revenues for Portugal as a whole as well as the Lower Mondego (Table 3B). However, this estimate does not take into account, for example, the non-use values. Additionally, fisheries or recreational activities were also not considered in the cost-recovery analysis because these activities do not involve extraction, regardless of the contaminants and pollutants that they may release into the water column (negative externalities).

3.4.2. Impacts upon non-use values (environmental integrity)

Along with the use values, the non-use values (essential to calculate the Total Economic Value) must be included in the analysis. However, due to data constraints it was not possible to calculate the values for all water-related assets. A Spearman

Table 5

European Environment Agency (EEA) classification with respect to the Nitrate + Nitrite (NO_3+NO_2) and Phosphate (PO_4) water concentrations, in μmol l^{-1} (surface and bottom), as well as BAT assessment of Ecological Quality Status (EQS) based on macrofaunal communities, during spring months (April to June) from 1990 to 2006 in four estuarine areas (E–Euhaline estuarine; PNA–Polyhaline North Arm; PSSA–Polyhaline sand South Arm; PMSA–Polyhaline muddy South Arm). EEA classification: black: Bad; medium-gray: Poor; dotted light-gray: Fair; light-gray: Good. EQS classification: dotted medium-gray: Poor; medium-gray: Moderate; dotted light-gray: Good; light-gray: High.

	NO_3+NO_2								PO_4									Benthic Macrofauna (EQS)			
	SURFACE WATER				BOTTOM WATER				SURFACE WATER				BOTTOM WATER								
	E	PNA	PSSA	PMSA	E	PNA	PSSA	PMSA	E	PNA	PSSA	PMSA	E	PNA	PSSA	PMSA		E	PNA	PSSA	PMSA
90					1,5	5,3	5,9	4,9					0,96	0,59	0,92	1,19	90	M	G	G	M
91																	91				
92					5,9	15,1	16,0	11,0					7,21	12,47	15,52	11,75	92	M	M	G	G
93																	93				
94																	94				
95																	95				
96																	96				
97																	97				
98					15,9	31,1	16,6	22,6					0,55	0,57	0,24	0,66	98	G	G	P	M
99																	99				
00					1,5	23,1	18,4	16,5					1,02	2,25	2,08	2,15	00	G	M	G	G
01																	01				
02					12,7	13,8	8,9	8,2					3,20	3,70	3,71	3,46	02	G	G	M	G
03	10,2	18,2	5,7	21,6	4,5	8,2	4,4	13,6	0,96	1,39	0,71	1,80	0,79	1,03	0,67	1,70	03	M	M	M	G
04	5,8	11,6	3,8	14,6	1,8	7,1	2,9	13,2	0,68	0,96	0,64	2,13	0,39	1,11	0,51	1,85	04	G	G	M	G
05	5,9	8,1	5,9	11,5	6,6	7,3	5,7	12,2	0,55	0,88	0,72	2,00	0,49	0,80	0,71	1,89	05	G	G	G	G
06	17,3	20,4	12,1	20,0	12,8	10,5	13,7	19,9	1,18	1,18	0,87	1,99	0,58	0,78	0,78	1,94	06	G	M	M	H

correlation analysis was performed to test (at a significance level of $p = 0.05$) the impacts between identified pressures and environmental assets (mostly nutrient concentration and physical parameters). The analysis crossed environmental assets (nutrients concentrations in the water column and water extraction) and drivers acting on the system (total population, urban land occupation, effluents produced, agricultural area and production, fisheries production and number of boats dedicated, industrial land-area, commercial harbour entrances and dredging activities, salt-works area and production, tourists numbers). It was possible to demonstrate that effluents production (from the several sources) and the reduction of activities belonging to the primary sector had a significant influence on water status (at $p = 0.05$). From this analysis, we could see important trade-offs and competing forces among activities in the estuarine area, especially between primary sector activities (such as fisheries or agriculture) and tertiary sector activities and social indicators (population indicators, tourist numbers, and effluent levels). A significant role of wetlands in highly nutrient-loaded agricultural catchments was also inferred. The existent positive relationship between organic matter percentage and agricultural production in estuarine areas, suggests that the parameter 'agriculture' may significantly impact water quality.

3.5. Socio-economic Responses

3.5.1. Policies and directives

The societal response emphasizes existing policies or programmes to reduce pressures and negative impacts acting on the ecosystem. A progressive increase in social drivers occurred during the study years concomitantly with a decrease in most economic drivers, especially those related to the primary sector (Table 6, "Trends" column). Due to uncertainty in the estimated area of land use, changes in the area dedicated to these activities must be treated with caution. The available data reflect the estimated changes in land-use patterns for ecosystem services (baseline scenarios). The selected indicators showed that agricultural area occupies the largest portion of the estuarine area (Table 6). This area has, however, decreased at an average rate of 5% per year (Table 6, "Trends" column). In contrast, the urban area has increased at an average rate of almost 8% per year (Table 6, "Trends" column). Assuming these trends for 2015, it is possible to see that special attention has to be given to activities and pressures coming from the social drivers, water uses, and activities as tourism or even commercial harbour (Table 6, "2015 scenario" column).

3.5.2. Management actions

When considering the scenarios trends and expected values for 2015 (e.g. increase of wastewater volumes), and combining it with the system knowledge, efforts were dedicated to better understand the water dynamics and related ecosystem functioning, with the intention of preparing management responses. After several events leading to the degradation of the Mondego Estuary ecological condition (e.g. eutrophication in 1993), in combination with the freshwater flow interruption into the estuary South arm, responses were targeted to prevent further environmental problems, rather than being conventionally, reactive. The restoration of the *Z. noltii* habitat was one example: in 1986, the estuary had 15 ha of highly productive meadows, but by 1997–1998, this area was reduced to 0.02 ha. In 2005, after the implementation of several mitigation

Table 6
Baseline 2015 scenario for the Mondego Estuary region, following the 2006 observed data and posterior trends (GDP: Gross Domestic Product) considering selected indicators of natural and anthropogenic (social, economic and ecological) drivers.

Drivers		Selected indicator	1994 data	2006 data	Trends (%/year)	2015 scenario
Natural	Natural					
	Invasive species[3]					
	Extreme events[3]					
	Floods					
	Drought					
Anthropogenic	Social					
	Population	Area (ha)	661.7[c]	1773.9[d]	7.9	6110.4
		Total population (n°)	61 830	63 372	0.16	64 386
		Population density (hab/Km^2)	163	167	0.17	170.04
		Households number (n°)	22 976	42 685	0.48	44 734
		GDP per capita	95.2	99.3	1.10	110.2
	Economic					
	Agriculture	Area (ha)[a]	272 107.7[c]	124 917.2[d]	−5.2	12 491.7
		Employment (n°)[b]	330 955	114 528	−7.27	31 266
		Explorations (n°)[b]	128 119	96 253	−2.77	69 591
		Output (t)[b]	925 227	875 781	−0.59	824 110
	Industry	Enterprises (n°)	7625	6714	−1.32	5828
		Employment (n°)	11 500	19 895	8.1	36 009.9
		Output (1000 €)	1 029 000	2 041 247	10.9	4 266 206.2
	Salt-works	Area (ha)	137	33	−8.4	5.28
		Units (n°)	83	15	−9.1	1.35
		Production (t/year)	1511	870	−4.7	461.1
	Tourism	Lodging capacity (n°)	2339	1499	−3.6	959
		Output (1000 €)	3271	6 849 000	10.9	14 314 410
	Fisheries	Employment (n°)	737	560	−1.7	465
		Fishing boats (n°)	319	211	−2.4	160
	Commercial harbour	Traffic (entrance n°)	269	363	7.0	617
	Ecological					
	Water extraction	Water volume (Hm^3)	4910	4877	−0.1	4828
	Wastewater	Drainage (Hm^3)	1586	2620	7.2	4506
		Treated (Hm^3)	0.539	2474	39.9	12 345

[a] For the Mondego Estuary only.
[b] Trends for the Centre region.
[c] 1990 data.
[d] 2000 data.

measures (1998), the *Z. noltii* area had recovered to about 4.2 ha (Patrício et al., 2009). Efforts have been dedicated to protect and restore this area, preventing future situations that could contribute to its further degradation or loss.

4. Discussion

4.1. Was DPSIR an appropriate tool to discern ecosystem-socio-economic interactions?

While analysing the integral system by the DPSIR framework for the Mondego Estuary, a clear picture arose: there are no linear relationships or direct cause-and-effect patterns among drivers, impacts, and status; the interactions among them are complex and at least cumulative (Fig. 4). The relationships, moreover, occur in addition to the natural variation (de Jonge et al., 2003; de Jonge, 2007). Three main sources of impact are acting upon the entire system. First, at the whole estuary level, diffuse pollution, is a major concern. Our case study clearly showed that the discharges might pollute, may be contaminate, the water courses and influence the estuarine water quality (illustrated by the significant Spearman relation between the produced volumes of urban wastes and the water quality). Inflows of water, nutrients and sediments from surrounding fields and activities greatly influence the overall water condition. Therefore, diffuse pollution, arising from catchment wide highly dispersed land use activities, can collectively have substantial impact on the ecosystem (WATECO, 2003). Discharges of contaminants and nutrients not only degrade the system (with an increase in primary production, higher oxygen demands and high organic matter contents) but also may lead to human health problems, such as contamination of (consumable and valued) bivalves. Second, at the North arm sub-system level, the physical interventions (sediment dredging and sand mining) are of particular importance. A mean annual dredging of about 1×10^6 m^3 yr^{-1} is considered necessary to maintain the Figueira da Foz harbour (Cunha and Dinis, 2002). Moreover, several barriers along the Mondego mainstream protect towns along the banks from floods; these include dams that control water runoff or excessive silting. Third, at the South arm sub-system level, the nutrient discharges may have important effects. Indeed, Baeta et al. (2009a; b) using stable-isotope analysis of the intertidal community has shown that the sources of nitrogen in this arm are coming from human activities. In fact, $\delta^{15}N$ values ranging from $+10$ to $+20‰$ in primary producers strongly indicate anthropogenic sources, whereas nitrate derived from atmospheric deposition produces values smaller than 6‰ (Kendall, 1998).

Aiming to integrate impacts and possible solutions, the DPSIR framework can be an effective tool to communicate complex interrelations occurring on a system (Turner et al., 2000). By its implementation we were able to identify the main relevant variables that can determine the systems' functioning and resilience ability. Nevertheless, and although it may be seen as simple to implement, this framework has revealed two main drawbacks: a) the weighting of pressures is difficult to estimate, not only due to multiple relations among factors, but also because it is difficult to determine which contribution may lead to what pressure (e.g. difficult to determine what nutrient percentage comes from agriculture fields, or from aquaculture, etc.); b) the cumulative interactions among the DPSIR categories are not fully taken into account (it is considered for the responses category, but there is not a clear relation among the other variables). Another criticism pointed out to the DPSIR approach is the absence of an explicit stakeholder role on the process, they may participate but the engagement cannot be described satisfactorily (Bruins and Heberling, 2005). In our study, the inclusion of the water uses and services approach within this framework was an attempt to suppress this drawback.

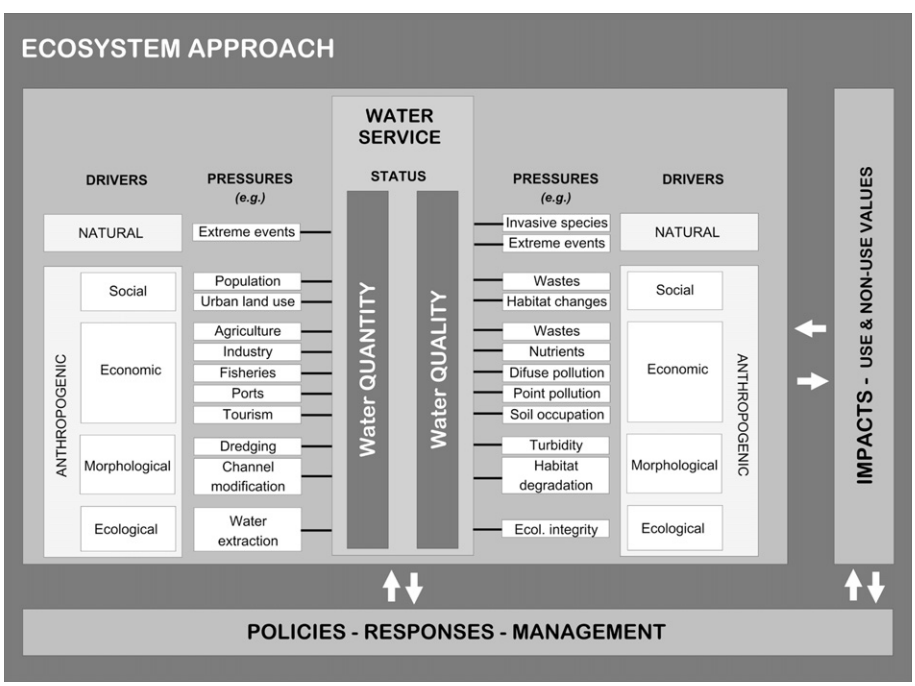

Fig. 4. The drivers and pressures acting upon bio-physical processes can lead to changes in the systems' functions and so change the outputs quality and quantity, resulting in a wide range of environmental impacts. Two main types of drivers were considered, Natural and Anthropogenic. Within the Anthropogenic Driver 4 sub-classes were distinguished (Social, Economic, Morphological, and Ecological). Some examples of pressures are illustrated in the diagram, showing the connection and influence upon the water service status (both quality and quantity). All these variations in the water service status will be reflected in the use and non-use values of the system. Responses allow integrating all these measures and interests into the management action more suitable for the estuarine system.

4.2. Is it possible to link wetlands functions and their economic valuation?

Water pollution from households and economic activities can cause severe degradation of water quality and can lead to significant changes in ecosystem structure and functioning and thus also functions. These changes and impacts ultimately reduce the overall ecosystem services. When the demand for certain services increases, human actions are often accompanied by the modification of ecosystems to increase their provisioning capacity. Although, in contrast to other estuaries worldwide with denser population and industry (e.g. Hu et al., 2001; Boyes and Elliott, 2006), the Mondego has been considered as a medium-sized estuary, nevertheless we recognized a strong social and economic functional dependence upon the estuarine region. The main aim of the valuation was then to indicate the overall economic efficacy of competing uses of the ecosystem resources. In general, water consumption increased with population and GDP. From 1994 to 2007, and following national and international trends, there was a decrease in the commercial fish catches parallel to a decrease in the number of fishing boats (MEA, 2005). This represents a 24% decrease of people employed in the fisheries sector. Between 2003 and 2007, the ship traffic in the harbour increased by almost 35%, mostly for transport purposes, which, despite the decreases in the fisheries sector, led to a higher-pressure intensity to the system over the years. These intrinsic trades-offs among activities create several pressures and impacts on natural resources. As environmental assets in general and water resources in particular are becoming increasingly precious goods, there is a need for further regulation to avoid market failures. Likewise, the increasing watershed and aquatic activities taking place along the estuary lead to higher water extractions, and possible higher water stresses. The drivers' analysis showed that concomitant with population growth there was also an increase in economic activities related to the secondary and tertiary economic sectors. This was clearly visible in the increasing employment rates for the industrial sector (despite a decrease in the number of tourists and industrial facilities) and in overall profits (109.4% and 98.4%, respectively). This implies an increasing demand for food, water supply, water usage, and wastewater discharges. A total wastewater drainage increase over the years was in fact observed already as a direct result of an increase in the social and economic drivers. Contrary to this there was a slight decrease in water extraction, which may be explained by the decreasing importance of mainly agriculture activities (primary sector) at all the considered scales. A key approach for preserving the wetlands is to maintain the quantity and quality of the water on which they depend. The observed pressures on water quality and estuarine resources mainly result from the choices society makes to economically develop and to conserve the watershed. Thus, the valuation of resources involves identification of the changes in economic costs and benefits due to changes in environmental assets. The flow of costs and benefits over time is used to determine the asset value of the resource. Water services can enter into an individual's utility function directly through consumption, indirectly through the household production function, or as factor inputs in production (Aylward, 2002). According to Henriques and West (2000), the total cost estimate must be based on the rigorous calculation of water services, environmental costs, and scarcity costs. From this analysis, it was only possible to calculate the water services. Nevertheless, there is much uncertainty regarding environmental costs and scarcity (Birol et al., 2006), which contributes to the inefficient use of water resources (Henriques and West, 2000). Still, the main objective of water valuation initiatives is to guarantee that water users and the general population are involved in conservation, either through a water use fee or by taking direct action to reduce pressures on water resources. Despite the controversy, it can be postulated that through the attribution of an economic value to water resources could be an effective way to protect and manage it (Young, 2005; Birol et al., 2006). Here the goal was not to attribute a total value to these resources because the intrinsic behaviour of biotic and abiotic components of water is too complex and intricate to be measured relying solely on a couple of ecosystem attributes. It is required to include in the future also other system components like e.g. fishes, plants, phytoplankton, etcetera.

4.3. Management concerns and recommendations

This study identified two main management concerns regarding the estuary:

1. An increase of economic activities that relies on a good system quality
   -Tourism/ecotourism activities: A strong seasonal variation in local population densities is observed. During summer months (June to September) a 47% increase in the number of tourists occurs (INE data). This leads to extra system pressures, not only due to the extra loads of pollutants, but also due to physical perturbations of the system. Although there is no shortage of water for any type of use in the Mondego catchment area, water quality is a matter of great concern, not only because of the population growth, but also because of the increase in activities which depend on aquatic ecosystems. Ecotourism projects for example have been developed for Murraceira Island (mostly bird-watching and traditional salt-extraction tours). These activities claim to promote economic and social development while also maintaining the ecological processes, the species structure, and the system functions to society.
2. The water quality improvement or/and maintenance
   -Habitat condition: A good system condition supports its optimal functioning and species structure. Based on the developed scenarios, the present impact on water quality can be expected to decrease, mostly due to management as human response actions, while changes in water allocation are more unpredictable. For example, the water turnover increase combined with a reduction in the nutrients discharges, mainly in the South arm sub-system, has created conditions for a better performance of the system. Furthermore, it was also verified that the decrease in agriculture might be compensated for by an increase in industrial activity and household consumption (both in water consumption as in effluents produced). With the agriculture activities reduction, it was expected to observe a reduction in the nutrient concentrations in the water column. However this was not observed, which reinforces the importance of activities trade-offs (e.g. agriculture reduction but industry and households increment) and even of the inherent ecosystem properties (nutrients remain in the sediments). River hydrology, water quality, and ecosystem integrity determine the catchment habitats', productivity, and supply. Any management action must take this reality into account.
   -Activities trade-offs: Salt production can be regarded as a 'less aggressive' system pressure than others because it maintains the diversity of the waders that use the Mondego Estuary during breeding and migration (Lopes et al., 2000; Pinto et al., 2010). From the considered activities occurring, the salt pans offer the more stable situation when considering the human–ecosystem interface. This traditional

activity is decreasing, as reflected in the area used and annual salt production. Nonetheless, this activity has a strong relationship with local fish farming, because areas for aquaculture are often converted salt-works. This physical replacement is a concern from the biodiversity perspective, because it implies extra, untreated organic loads into the estuary. Agricultural practices are also a major concern for ecosystem management. Intensive agriculture has strong environmental impacts through high fertiliser quantities, usually nitrogen compounds and phosphate, which promote rapid development of opportunistic macroalgae (Rocha and Freitas, 1998). This situation can lead to significant impacts on the native biodiversity because it reduces the natural barriers and intrinsic resilience of the system (Tilman, 1996; Rocha and Freitas, 1998).

- Production of goods/human welfare: A poor status of the water quality is going to influence and determine local/traditional activities, that although may not substantially contribute to the national economy, may have a strong local importance (e.g. manual and commercial cockle harvesting). The decrease in production of these species (mostly *Cerastoderma edule*) affects the socio-economic conditions of a part of the local population, since this activity is a highly valued good.

In general we observed that ecologically the system has recovered over the years. However, in more detail, it is possible to see that the overall situation of nutrient concentrations has only slightly improved. This places the system into an elusive situation, where if by chance the mitigation measures do not work as predicted, it may return to the degraded initial condition. The implemented mitigation measures solved existing eutrophication symptoms, mainly by changing the water circulation inside the southern arm which resulted in a reduced water residence time. There were no changes observed into the agriculture practices, and nutrients remained at similar concentrations in the water column. Those solutions do not offer a final solution to the existing problems. Therefore, assuming that the goal is the 2015 established scenario (achievement of a Good Ecological Quality Status), and from the observed trends for both drivers/pressures and status evolution obtained from the DPSIR analysis, alternative recommendations of actions are required. Examples are:

1. Creation of buffer zones for the extraction of the nutrients added by mainly inadequate agriculture practices. Former agriculture fields could simply be used as water pathways where nutrients could sink/be removed from the water before it is discharged in the estuary. The application of the EcoWin2000 model for the Tagus estuarine system, for example, demonstrated that the nitrogen removal by salt-marshes (with a total area of approximately 8.2×10^6 m^2) is equivalent to the loadings from about 400 000 people (20% of total population in the estuarine surroundings) (Simas and Ferreira, 2007). This sort of option may contribute to reducing costs from wastewater treatment plants functioning;
2. Higher control and management of surrounding activities. To ensure that impacts and effects (e.g. nutrient loads) on the system remain within tolerable limits, the application of pro-environmental taxes to economic activities or even to the population involved in the production of effluents could be considered;
3. Promotion of pro-environmental activities that, although still using the system and occupying its areas, could have a lower environmental impact on the overall system quality (e.g. ecotourism activities or certifying of salt production companies), instead of invasive activities. A possible activity could be, for example, the cultivation of bivalves. Assuming that the capacity of the bivalves to extract nutrients from the water column is sufficient (Ferreira et al., 2007), a more intensive production of these assets would imply an added socio-economic value.

To adequately manage the ecosystem, policymakers should have to consider the conservation of the system assets, along with its sustainable use. Socio-economic and environmental compromises need to be made, aiming at system preservation along with efficient supply of services. The development of scenarios might be another useful tool for water resource management in order to:

- achieve efficient supply and allocation of resources while guaranteeing their rational use;
- promote sustainable exploration of existing resources; and
- minimise the direct and indirect costs associated with its use and conservation, while assuring overall economic development (Manoli et al., 2005).

Changes in land use, future development and urbanisation pressures, and the increased use of water, as shown by the baseline scenario, may result in threats to the estuarine environment. However, it should be highlighted that external factors, such as the current economic crisis, were not considered in the scenario development and that this may have influenced the final outcome as well. It is important to regulate new pressures to ensure that no deterioration in status occurs, while minimizing present pressures. Continuous monitoring and controlling of pollution within aquatic ecosystems is essential to facilitate the selection of the most reliable and efficient methodology. The overall societal response to water pollution and nutrient enrichment is characterised by several conflicting factions, ranging from farmers to public drinking-water constituents, and from water-related recreationalists to environmentalists. Among this wide range of interests, policymakers at different administrative levels should try to find a compromise between both private and public goods for an efficient and consensual water management program. Understanding the complex and intricate trade-offs among ecological, social, and economic goals is fundamental in designing and implementing management policies and for ecosystems restoring (Marques et al., 2009).

5. Conclusions

Analysis of the relations between the main services and uses provided by estuarine systems assessed that the factor water quality improvement was most strongly influencing estuarine functioning within the related ecological and socio-economic spheres.

The results illustrate that the integration of information by applying the DPSIR approach provides a common framework of analysis that benefits 1. better management actions, 2. weighting activities trade-offs (e.g. salt pans and aquaculture), 3. societal actions to be taken, 4. gap analysis studies, through the identification of the major driving forces acting on systems, 5. ways to deal with it, and 6. execution of monitoring to follow it.

The application of the DPSIR approach identified two main future research topics 1) The need for a quantitative ecological approach (e.g. catchment model) including the determination of flows and values of each service in addition to the present qualitative one (which factors and how they interact); and 2) The need for integrating more components of the integral system than we did so far (e.g. fishes, geographical, cultural values) and that strongly contribute to the estuarine functioning.

Ethical statement

We declare that this work is an original research carried out by the authors and is not being considered or submitted for publication elsewhere. All authors agree with the contents of the manuscript and its submission to the journal. No part of the research has been published in any form elsewhere. All sources of funding and the people who have contributed to this paper are properly acknowledged in the manuscript.

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