Scenario Analysis in Ria Formosa with EcoDynamo

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June 2006

DITTY (Development of an information technology tool for the management of Southern European lagoons under the influence of river-basin runoff)

(EESD Project EVK3-CT-2002-00084)

Summary

Ria Formosa is a natural park managed partly by the Portuguese end-users of the DITTY project – Ria Formosa Natural Park authority, under “Instituto para a Conservação da Natureza (ICN)”. There are many conflicting interests over the management of this important coastal area: fishing, tourism, aquaculture, salt production, harbour activities, urban development and conservation. Furthermore, several institutions, such as the Natural Park Authority, municipalities, the Portuguese Navy, just to mention a few, are involved in decision-making over several areas of the natural park. Within DITTY, several scenarios were selected among those relevant for the management of this coastal ecosystem, considering available information from the end-users, relative importance of the mentioned scenarios, modelling and time constraints.

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1 Introduction

1.1 Brief environmental, socio-economical context

Ria Formosa is a shallow meso-tidal lagoon located at the south of Portugal (Algarve coast) with a wet area of 10 500 ha (Fig. 1-1). The lagoon has several channels and an extensive inter-tidal area, around 50% of the total area; mostly constituted by sand, muddy sand-flats and salt marshes. Due to its gentle slopes, inter-tidal areas are exposed to the atmosphere for several hours over each semi-diurnal tidal period. Tidal amplitude varies from 1 to 3.5 meters and mean water depth is 3.5 m (Falcão et al., 2003).

The main urban centres of Ria Formosa are Faro, Olhão and Tavira. Since 1981, resident population has been growing up (Table 1-1). The city with the highest number of inhabitants is Faro, whereas the municipality of Tavira has the minor resident population.

In summer, there is a three fold population increase due to tourism (Mudge & Bebbiano, 1997). It is remarkable that the population centres located along the barrier island system, separating the lagoon from the open sea also have an extremely variable annual population depending on their main economic activities: tourism, fishing, commerce and shellfish. These population shifts present a complex problem in terms of waste water treatment facilities (WTP). There are plans to reduce the number of WTP and increasing their individual capacity.

Dredging operations have been carried out to permit the access to the Faro-Olhão harbour. These operations tend to concentrate along the main navigation channels and inlets. They are expected to produce hydrodynamic and biogeochemical impacts. There are also economic interests involved due to the value of sand for the building industry.

Shellfish culture has an important contribution to Algarve's economy, with approximately 10000 people directly or indirectly involved in this activity (POOC, 1997). Species of high economic value, like the clam (*Ruditapes decussatus*), and the oyster (*Crassostrea angulata*) are cultivated in the lagoon inter-tidal areas where, approximately, 1587 concessions for clam growth banks are in activity (Cachola, 1996). The annual production of clams reaches 5000 tons year^{-1}, which represents 90% of the regional production, while oyster production is approximately 2000 tons year^{-1} (POOC, 1997).

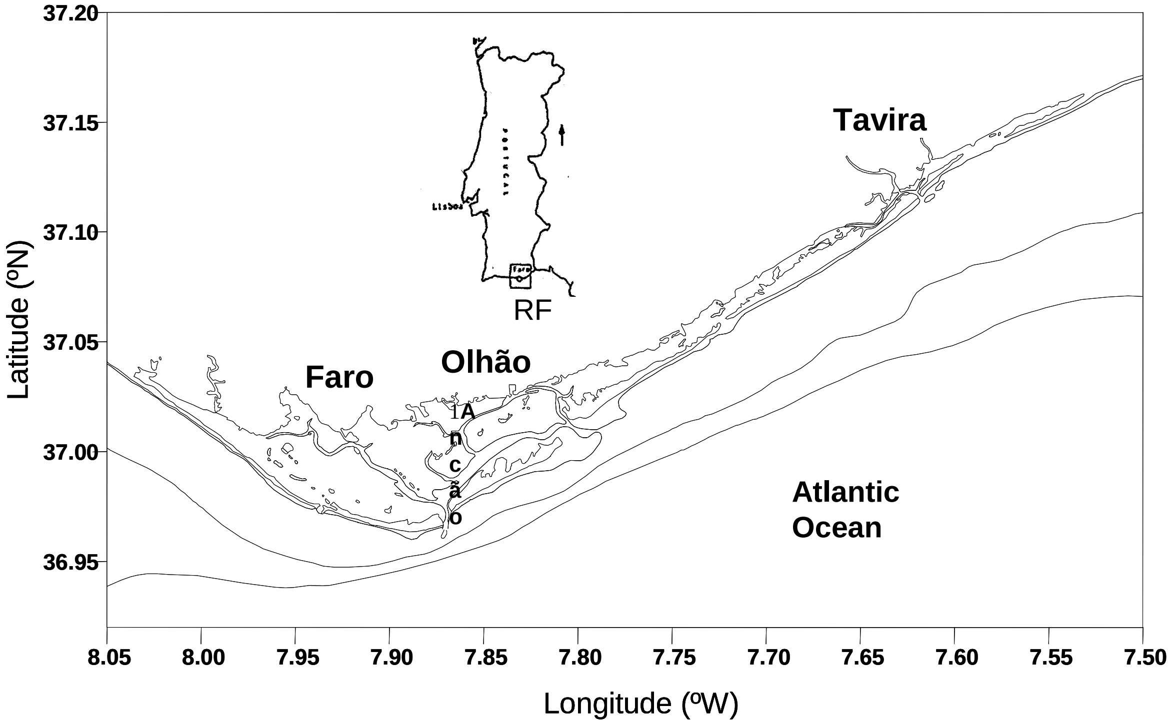

Figure 1-1- Geographic location of Ria Formosa.

Table 1-1 - Evolution of Ria Formosa resident population.

Municipality	**Resident population** (nr. of inhabitants)		
	1981	**1991**	**2001**
Faro	45 109	50 000	58 800
Olhão	34 573	37 500	41 000
Tavira	24 615	25 000	25 000

Source: http://www.ine.pt

Reclamation of salt-marshes for building marinas and other facilities is an important threat that should be considered in this work, given its potential implications over biogeochemical functioning of the ecosystem. The opposite trend of recovering former salt-marsh areas from abandoned salt-ponds may be an interesting management option.

1.2 Identification of environmental concerns and management options

Following the environmental and socio-economic contexts referred above (for more details refer Falcão et al. (2003)) and after extensive debates between all Portuguese DITTY partners, some environmental concerns and management options were selected for analysis within the project framework. Concerns have to do mostly with potential changes in water quality and bivalve production resulting from different management options. These are mostly related to decisions about dredging some channels, increasing bivalve cultivation areas, changing the number and location of WTPs and increasing/decreasing salt-marsh areas. In order to synthesise these concerns and management options the DPSIR framework was used across all DITTY partners. Its implementation for Ria Formosa is described in the Methodology section (cf. – 2.1).

1.3 Objectives

This work represents the first approach to the scenario analysis of Ria Formosa and its objectives are to analyse management options suggested by the end-users, such as:

(i) Changes in bivalve cultivation densities;

(ii) Improvements in WTP performance;

(iii) Changes in lagoon bathymetry resulting from dredging operations.

2 Methodology

In the next paragraphs, a brief description of the methodology followed to define scenarios and proceed with their analysis will be given. This will start with the description of the DPSIR framework application, followed by a reference to the model and variables used, the temporal and spatial scales considered and the specific scenarios analysed in the present report.

2.1 DPSIR

Table 2-1 synthesises the "**D**rivers", "**P**ressures", "**S**tates", "**I**mpacts" and "**R**esponses" considered for Ria Formosa. Table 2-2 synthesises sets of scenarios to be analysed in relation to each driver and corresponding environmental indicators and management options. Hereafter each set of scenarios will be referred by their number as in Table 2-2.

Table 2-1 - DPSIR scheme at the coastal lagoon level.

Driver	Pressure	State	Impact	Response
Bivalve farming	Sand addition to tidal flats Changes in the areas of bivalve farming Changes in bivalve density	Sediment level Sediment area Bivalve quality, quantity and mortality	Changes in the bathymetry Water quality Bivalve production	Sustainable bivalve farming (special attention to the addition of sand to tidal flats and the carrying capacity of sediment)
Use of salt marshes	Building of: tourist structures (hotels, tourist villages, and facilities) Navigation facilities (fishing harbours and marinas) Recovery of salt marsh areas (from: deactivated salt ponds, fishponds and degraded areas)	Changes of salt marsh areas Changes of lagoon water quality	Water quality Changes in the biogeochemical cycles Changes in ecosystem productivity	Sustainable tourism and navigation (preservation of salt marsh areas) Improve the management of salt marshes area (recovery of degraded areas)
Population (resident and non resident-tourism)	Increase of resident population Changes of non-resident population Wastewater discharges	Water quality – (loads of nitrogen, phosphorus and faecal coliforms)	Pollution Eutrophication Bivalve contamination	Technical improvement of Waste Water Treatment Plants and interdiction of bivalve farming in areas under the influence of the waste water plumes
Water circulation	Changes in water quality	Bathymetry Water residence time Tidal currents	Changes in the environmental conditions	Sustainability of the ecosystem

Table 2-2 - Scenarios and management options defined by the end-users.

Nº	Driver	Scenario	Environmental indicator	Management options
1	Bivalve farming	Changes of bivalve biomass – increase/decrease/unchanged Changes of tidal flats level by addition of sand- increase/unchanged Changes of the areas of bivalve farming- increase/decrease/unchanged	Condition index, mortality of bivalves, oxygen consumption Oxygen penetration in sediment (biogeochemical processes) Losses and gains of tidal flats	Permission for bivalve farming: Increase/decrease the area of bivalve farming Increase/decrease bivalve density
2	Use of salt marsh areas	Changes of salt marsh areas due to economic activities (tourism and navigation) and salt marsh recovery – unchanged/decrease/increase	Productivity of lagoon water Changes in the biogeochemical processes	Permission for tourism and navigation facilities Salt marsh recovery
3	Population (resident and non resident-tourism)	Reallocation of Waste Water Treatment Plants and changes in their number decrease/unchanged	Nitrogen, phosphorus, faecal coliforms loads Solid waste production	Changes of treatment plants location and of discharge flows
4	Water circulation	Depth and width of lagoon inlets and some channels Increase/decrease/unchanged	Tidal currents Bathymetry Water residence time	Dredging Opening and close of inlets

2.2 Models, processes and variables

The model used for scenario analysis was implemented with EcoDynamo (Pereira & Duarte, 2005). It is a coupled hydrodynamic-biogeochemical model. Implementation, calibration and validation of the hydrodynamic sub-model were described elsewhere (Duarte et al., 2005).

Regarding the biogeochemical sub-model, it has been described in other reports (Chapelle et al., 2005a and b, Duarte et al., 2006). Water temperature is calculated from standard formulations described in Brock (1981) and Portela & Neves (1994). Water column biogeochemistry is simulated according to Chapelle (1995) for nitrogen, phosphorus and oxygen. Processes such as mineralization of organic matter, nitrification and denitrification were considered for nitrogen. Total and organic particulate matter concentrations (TPM and POM, respectively) are simulated following Duarte et al. (2003). Particulate organic matter (POM) is mineralized to ammonium nitrogen as described in Chapelle (1995). Oxygen is consumed in mineralization and nitrification and exchanged across the air-water interface. For more details on the ecological model and a complete listing of equations and parameters refer to Chapelle et al. (2005a and b). For macroalgae, the work of Serpa (2004) was used and for the sea grass *Zostera noltii*, the work of Plus et al. (2003) was followed.

Table 2-3 – EcoDynamo objects implemented for Ria Formosa (see text).

Object type	Object name	Object outputs
Objects providing forcing functions	Wind object	Wind speed
	Air temperature object	Air temperature
	Water temperature object	Radiative balance between water and atmosphere and water temperature
	Light intensity object	Total and Photosynthetically Active Radiation (PAR) at the surface and at any depth
	Tide object	Tidal height
Objects providing state variables	Hydrodynamic 2D object	Sea level, current speed and direction
	Sediment biogeochemistry object	Pore water dissolved inorganic nitrogen (ammonium, nitrate and nitrite), inorganic phosphorus and oxygen, sediment adsorbed inorganic phophorus, organic phosphorus and nitrogen
	Dissolved substances object	Dissolved inorganic nitrogen (ammonium, nitrate and nitrite), inorganic phosphorus and oxygen
	Suspended matter object	Total particulate matter (TPM), Particulate organic matter (POM) and the water light extinction coeffcient
	Phytoplankton object	Phytoplankton biomass (*PHY*) in carbon, nitrogen, phophorus and chlorophyll units and productivity
	Macrophyte and macroalgae objects	Macrophyte(*Zostera nolti*) and macroalgae (*Ulva sp.* and *Enteromorpha sp.*)biomass and productivity
	Clams *(Ruditapes decussatus)* object	Clam size, biomass, density, filtration, feeding, assimilation and scope for growth

The model is forced by tidal height at the sea boundaries and river discharges. These were calculated from meteorological and watershed data with the SWAT model (for details see Guerreiro & Martins, 2005).

EcoDynamo was implemented using the object oriented programming paradigm as described in Pereira & Duarte (2005). Implemented objects and corresponding simulated biogeochemical processes and variables are synthesized in Table 2-3.

2.3 Spatial and temporal scales

The spatial and temporal scales used for scenario analysis depend on the type of scenario. In those situations where a full hydrodynamic simulation is required, the domain corresponding to the rectangle shown in Fig. 2-1 is used, with a 3s time step. In this case, it is important to include a part of the coastal area bordering the southern limits of the lagoon and force the model along the western, southern and eastern-sea borders with a variable water level boundary (Duarte et al., 2005). With EcoDynamo it is possible to run only a part of the model domain, by defining a sub-domain (Pereira & Duarte, 2005; Duarte et al., 2006). This is particularly useful when several simulations may be run with the same hydrodynamic conditions. In this situation, time integrated current velocity values may be obtained by running only the hydrodynamic sub-model and then these values may be reloaded to force the transport processes, when running the biogeochemical sub-model, without the overhead of computing hydrodynamic processes. This approach has been used for all scenarios, when emphasis was on biogeochemical processes, with important gains in time due to the smaller number of cells of the sub-domain covering only the lagoon area and the larger time step used – 30 s. Hereafter, this will be referred as the “offline mode”. Temporal scales covered by simulations ranged from one month to one year. Spatial resolution is 100 m, over a finite differences model grid for all simulations.

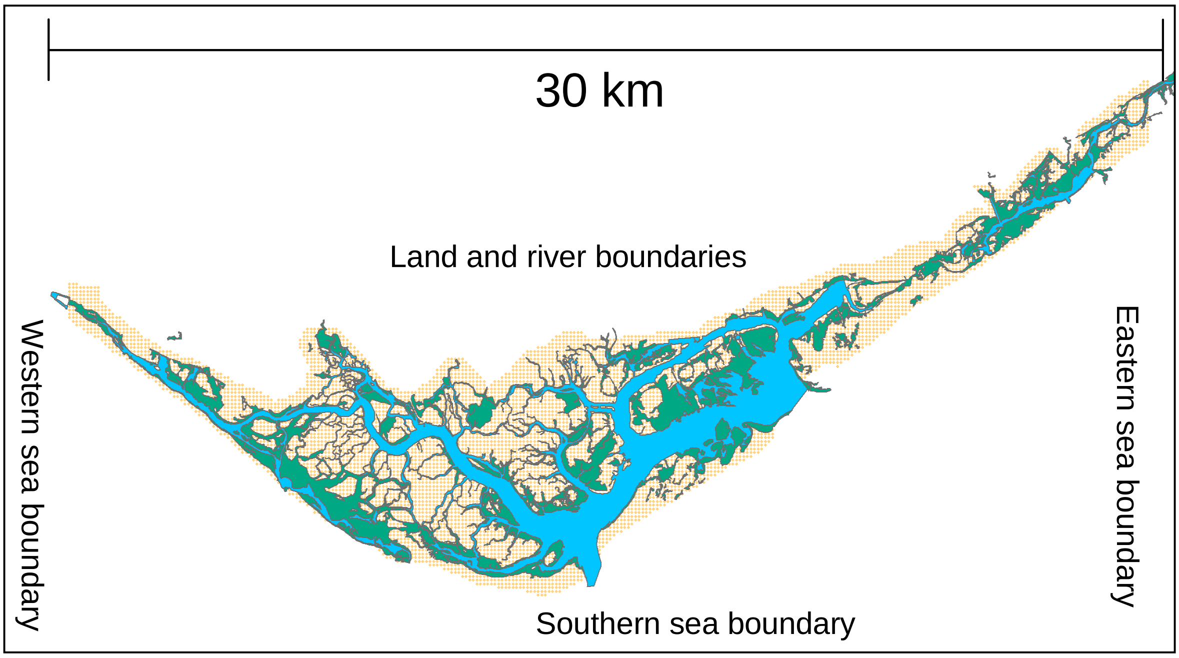

Fig. 2-1 – Model domain covering a total area of 546 km^2 (whole rectangle) and 98 km^2 (only the area of covered by the lagoon), for the hydrodynamic and biogeochemical simulations, respectively. Spatial resolution is 100 mm. Time step is 3 and 30 seconds for the hydrodynamic and the biogeochemical simulations, respectively (see text).

2.4 Description of scenarios analysed

The scenario analysis presented in this report includes the four scenario sets (1 – 4) depicted in Table 2-2, without a complete analysis of all possible scenarios within each set. In fact, the large computing time required for the model simulations, prevented a more detailed analysis. However, scenarios analysed so far were chosen for their larger importance and represent a significant part of all possible management options suggested by end-users.

The simulations were designed to understand the relative contribution of specific processes within the western part of Ria Formosa (Fig. 2-1), according to the objectives referred above (cf. – 1.3 Objectives), and may be viewed as a “virtual” experiment, with a few simplifying assumptions. Water quality data for the rivers draining to Ria Formosa, inside the lagoon system and at the sea boundaries, were obtained in several works carried out by the Marine Research Institute (Falcão & Vale, 1990; Vale et al., 1992; Falcão & Vale, 1995; Falcão, 1997, Falcão & Vale, 1998; MAOT, 2000; Falcão & Vale, 2003; Newton et al., 2004).

2.4.1 Scenario set 1 – Bivalve farming

Scenarios analysed are related to changes in clam (*Ruditapes decussatus*) density (cf. Table 2-2). Current cultivation densities correspond to 400 bivalves per square meter over the cultivation areas (Fig. 2-2). Simulations were carried by increasing it two and three fold. Obtained results were compared with a standard simulation (with the “normal” density) in terms of bivalve growth and water quality parameters – ammonium, oxygen, particulate matter and phytoplankton concentrations.

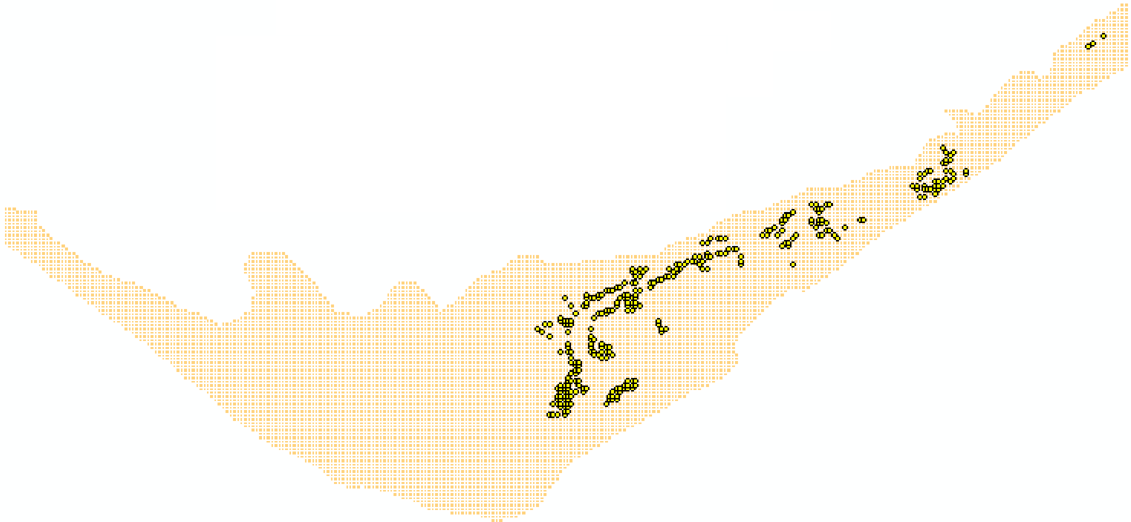

Fig. 2-2 – Spatial distribution of bivalve (*Ruditapes desussatus*) rearing areas in Ria Formosa.

2.4.2 Scenario set 2 – Use of salt-marsh areas

In the present model, salt-marshes are not explicitly represented as a state variable, acting as a forcing function though imposed particulate matter and nutrient exchanges (Duarte et al., 2006). Simulations were carried out with and without salt-marshes and by changing their influence on lagoon biogeochemistry though nutrient uptake rates, within ranges measured experimentally (Falcão et al., unpublished). In fact, salt marshes were used in model calibration due to the large uncertainties in their net exchanges with surrounding water.

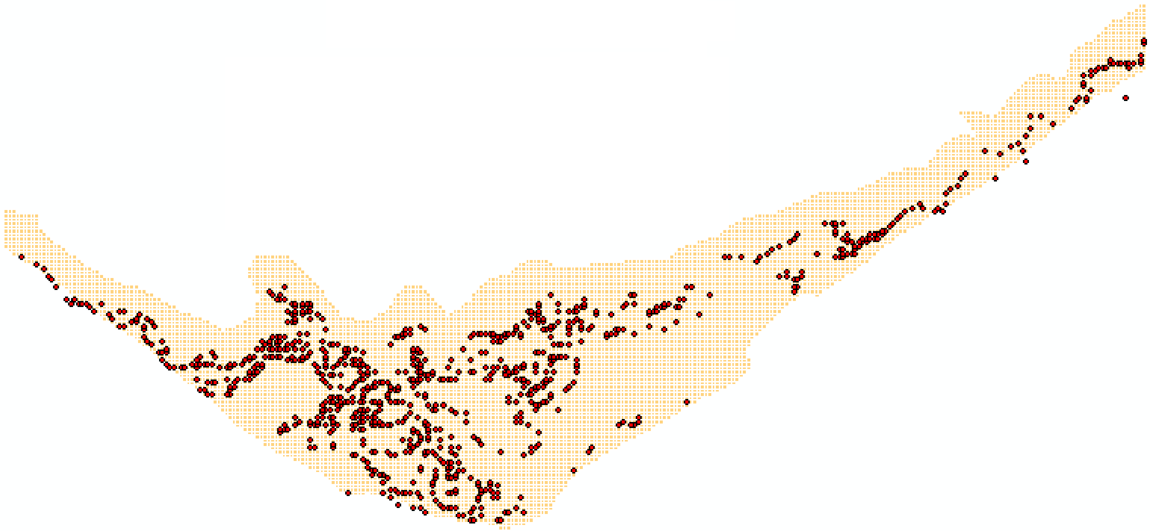

Fig. 2-3 – Spatial distribution of salt-marshes in Ria Formosa.

2.4.3 Scenario set 3 – Population / Waste water treatment

The present simulation set was not carried out with full model complexity. Only the "Wind", "Air temperature", "Water temperature", "Tide", Hydrodynamic 2D", "Dissolved substances" and "Suspended matter" objects were considered (cf. – Table 2-3).

Simulations (Table 2-4) were performed to understand the relative importance, on Ria Formosa water quality, of flow discharges from rivers and from WTPs, and of conservative and some non-conservative processes. In this case, the offline simulation mode was adopted – by running biogeochemical processes with previously recorded current velocity data (cf. – 2.3). The emphasis of this simulation set was put on WTP and river effects because both represent some of the most important influences of human population on lagoon biogeochemistry. Investigating their relative importance may help to understand the relative importance of future management options at the watershed level and regarding the number, location and treatment level of WTPs. Two contrasting river flow situations were considered – winter and summer - estimated with the SWAT model (cf. – 2.2). Comparing results obtained with different river discharge regimes (nearly zero discharge for the summer situation) or/and WTP discharges permits to understand the relative contribution of land drainage and WTPs to water column nutrient and suspended matter concentrations. Contrasting conservative with non-conservative simulations allows understanding the relative importance of water column biogeochemistry in explaining variability of those variables. When "Suspended matter" object is treated as conservative, POM is not mineralized to ammonium and phosphate. When “Dissolved substances” is treated as conservative, ammonium may increase due to POM mineralization, but nitrification and denitrification do not occur. In all simulations, the model was initialized with values well within the range of those observed in Ria Formosa and obtained from a data base created within the DITTY project (http://www.dittyproject.org/). Both simulation sets were run to simulate a period of one month.

Furthermore, WTP location was analysed in the light of water residence times calculated with the model for different areas of the lagoon to access their dilution capacity. Water residence times were calculated with the hydrodynamic model as described previously (Duarte et al., 2005). Table 2-4 synthesis simulations used for this scenario set.

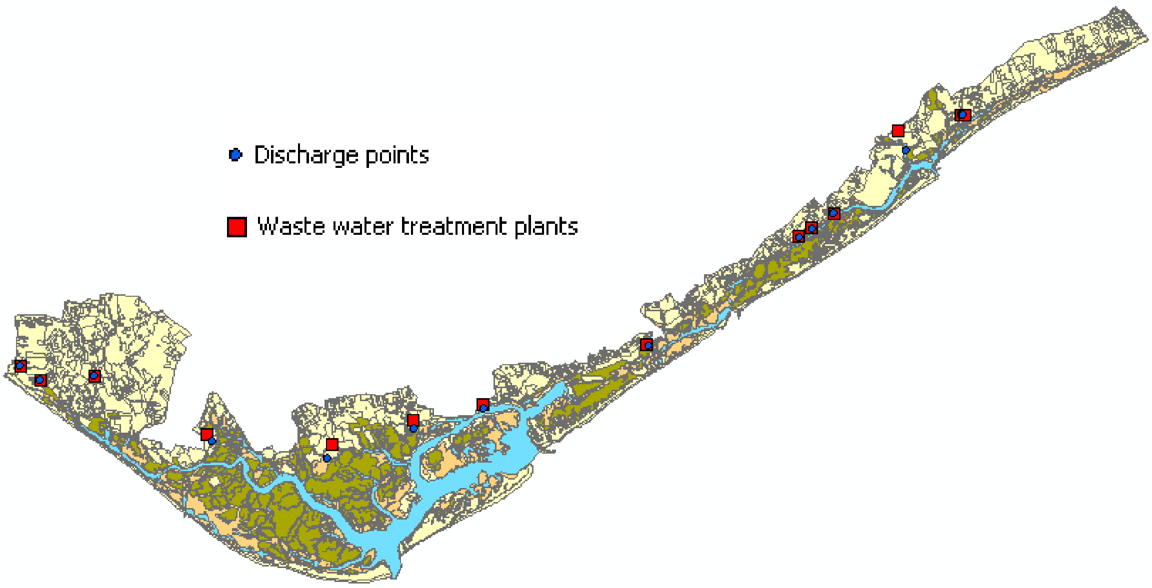

Fig. 2-4 – Waste water treatment plants (WTP) and respective discharge points in Ria Formosa.

Table 2-4 – Synthesis of some simulations analysed in the present work with simplified biogeochemistry, designed to evaluate the relative importance of river discharges and WTP loads in some water quality variables. For conservative simulations a zero value was assumed for all biogeochemical rate constants regarding mineralization, nitrification and denitrification. For non-conservative simulations the values reported in Chapelle (1995) were used with oxygen and temperature limitation (cf. – Methodology – Simulations).

Simulation nº	Discharges		Type Conservative Non-conservative
	River discharges	**WTP discharges**	
1	Winter	Yes	Conservative
2	Winter	No	
3	Summer	Yes	
4	Summer	No	
5	Winter	Yes	Suspended matter object non-conservative Dissolved substances object conservative
6	Winter	No	
7	Summer	Yes	
8	Summer	No	
9	Winter	Yes	Suspended matter object conservative Dissolved substances object non -conservative
10	Winter	No	
11	Summer	Yes	
12	Summer	No	

2.4.4 Scenario set 4 – Water circulation

These scenarios reproduce changes in lagoon bathymetry and/or inlet width resulting from hypothetical dredging and sediment accretion operations within some areas (Fig. 2-5). The details on each scenario are shown in Figs. 2-5 – 2-8, including the locations of the dredging operations and depth to which channels were "virtually" dredged. Ramalhete and Fuzeta channels (Figs 2-6, 2-7 and 2-8) have depths between c.a. 0 and 3 m. After the virtual dredging their depth would be 2 m and a new inlet is created in Fuzeta. In the Olhão channel, dredging to 8 m (Figs. 2-5 and 2-7) would correspond to more than a two fold increase in original depth for most of the channel area. In the case of "Fortaleza cultivation area scenario" (Figs. 2-5 and 2-7), the change corresponds to sediment accretion until a level above the hydrographic zero. This is to simulate a current practice among bivalve producers of adding sand to their rearing areas, in order to improve sediment quality for bivalve growth. Regarding "Faro-Olhão inlet scenario" (Figs. 2-5 and 2-7), the change corresponds only to an increase in inlet width by c.a. 100 m.

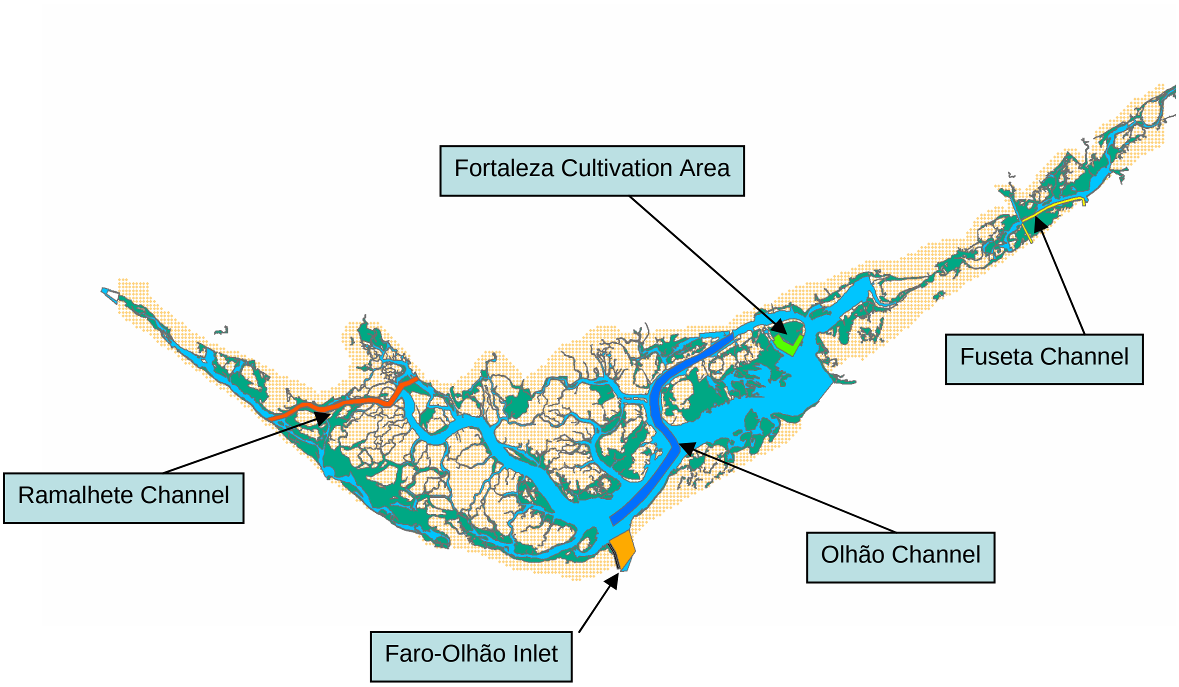

Fig. 2-5 – Location of the considered scenarios.

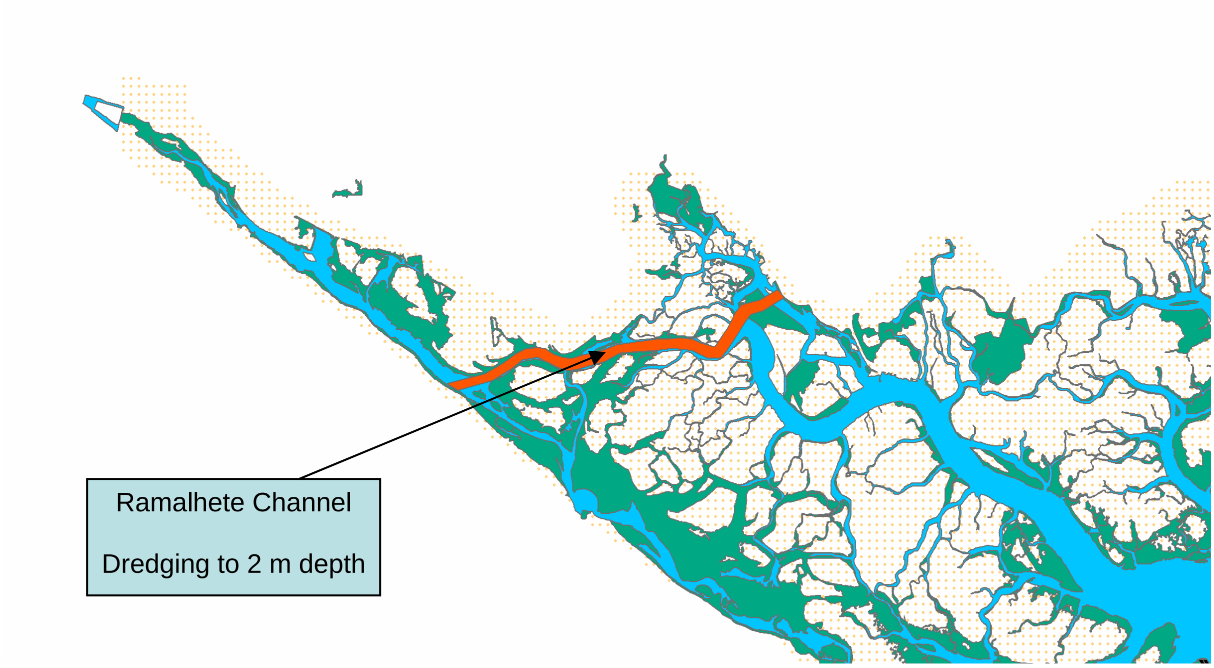

Fig. 2-6 – Ramalhete Channel dredging scenario.

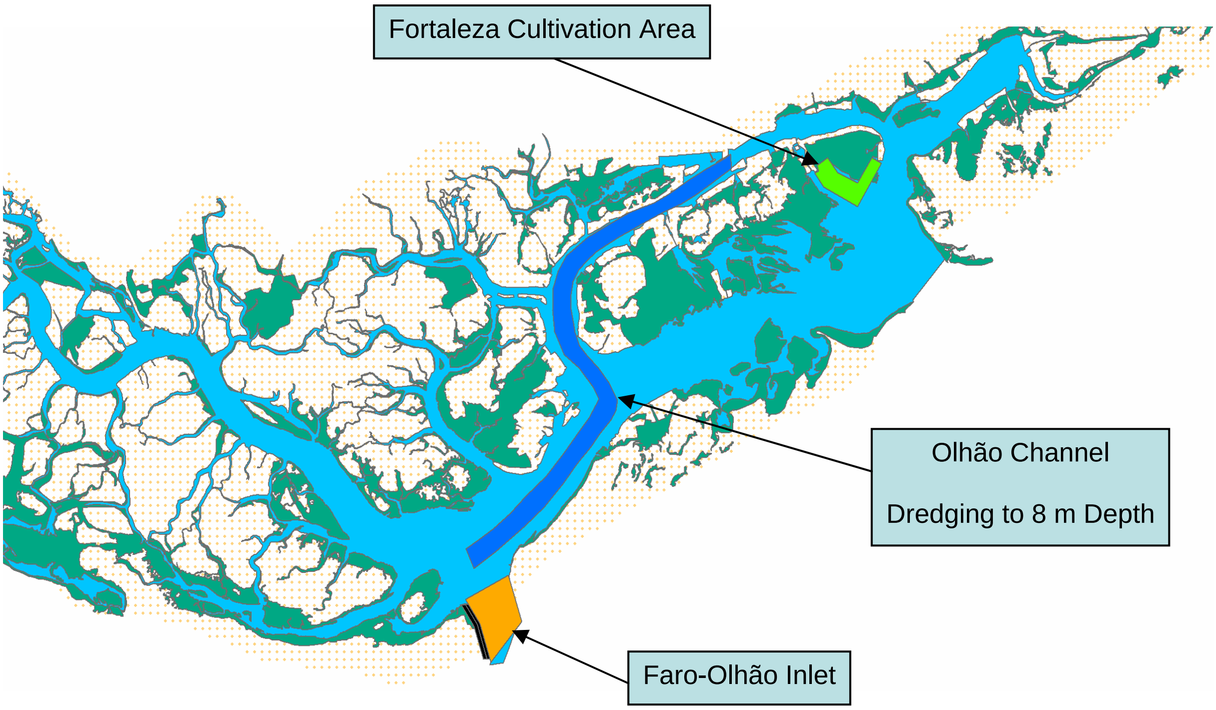

Fig. 2-7 – Olhão channel, Faro-Olhão inlet and Fortaleza cultivation area scenarios.

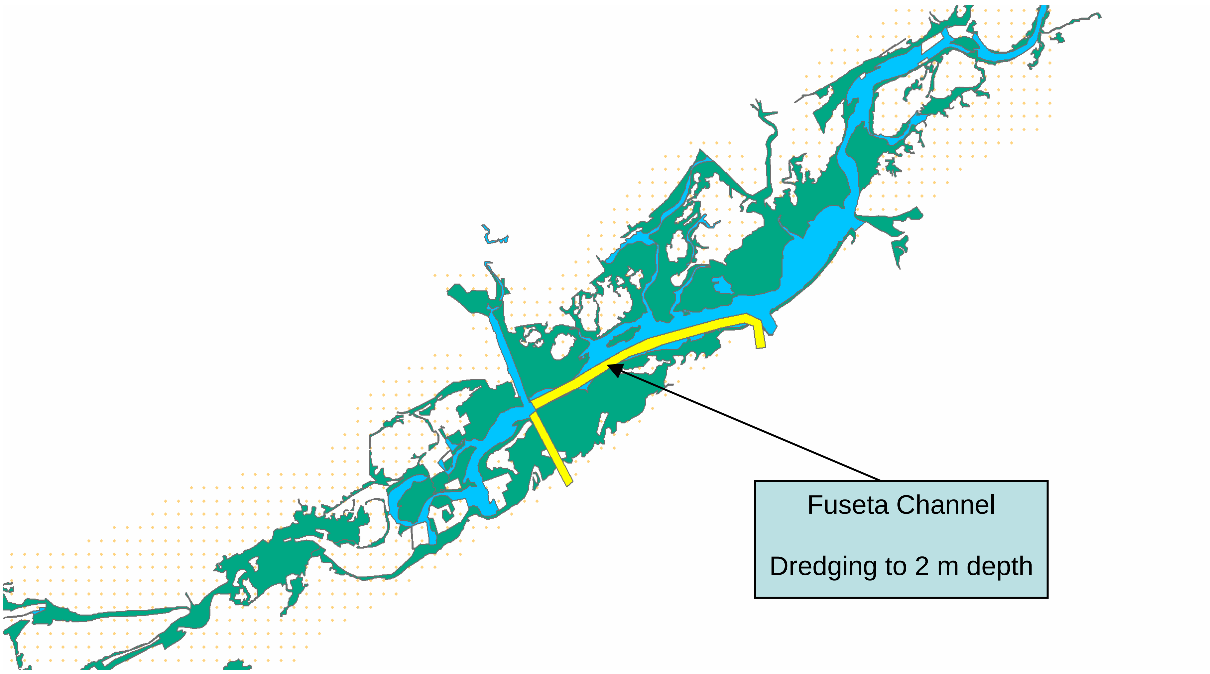

Fig. 2-8 – Fuseta channel dredging scenario.

Results obtained for each scenario, with the hydrodynamic and the biogeochemical model (offline simulation mode – cf. – 2.3), were compared with model validation regarding current velocity and tidal height at current meter and tidal gauge stations, depicted in Fig. 2-9, and water quality and sediment variables. Furthermore, monthly integrated residual input and output flows were obtained for all simulations.

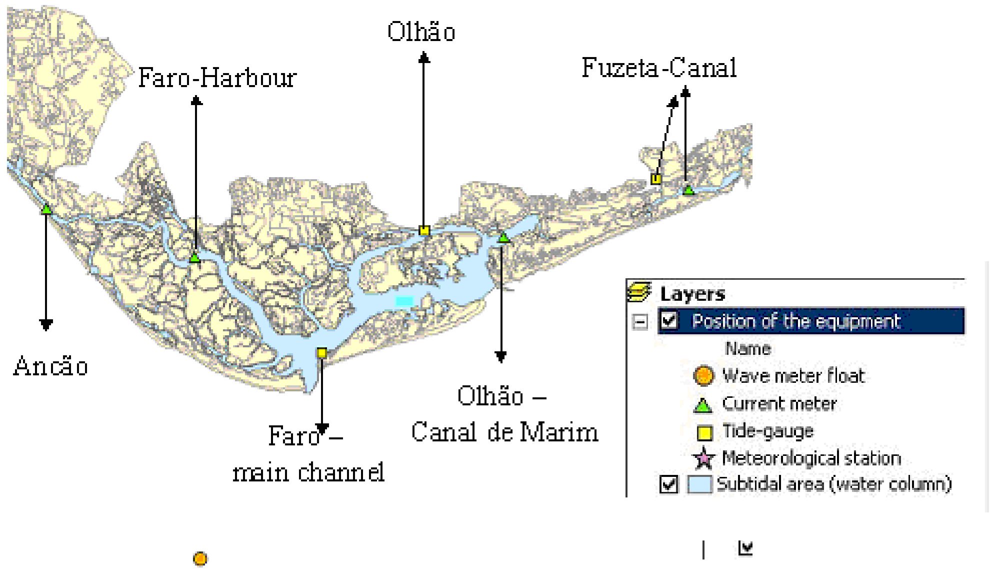

Fig. 2-9 – GIS image showing the location of current meter and tide-gauge stations surveyed by the Portuguese Hydrographic Institute in 2001 (IH, 2001) and used for model calibration (see text).

3 Results and discussion

3.1.1 Scenario set 1 – Bivalve farming

Table 3-1 summarizes results obtained with simulations carried out with different *R. decussatus* densities - ranging from a biomass of 1 till 3 kg (fresh weight) m^{-2} – regarding ammonium, oxygen, particulate organic and total matter concentrations and clam biomass, averaged over a period of one month, for bivalve rearing areas (Fig. 2-2). Obtained results suggest that increasing bivalve biomass leads to an increase in ammonium and a decrease in all remaining water quality variables, over bivalve rearing areas.

The increase in ammonium corresponds to a clear worsening of water quality, especially at the higher clam density, when more than a two fold increase is predicted by comparison with the simulation under a normal biomass density. Furthermore, it is apparent that the increase in initial biomass is not followed by an increase in average biomass in the same proportion. In fact, comparing the former with the latter, for the “normal density” and “triple density” simulations, suggests that a three fold increase in initial biomass leads to a c.a. two fold increase in average biomass (used here as a surrogate for production). Therefore, increasing bivalve biomasses within the limits tested so far implies reducing significantly bivalve growth, due to food limitation, and worsening water quality. This reduction in bivalve growth is in accordance with farmer's experience, suggesting that increasing cultivation density over 1 kg (fresh weight) m^{-2} leads to increased mortality. This increased mortality may be, partly, explained by the predicted decreases in water quality and food availability.

The relative reduction in particulate organic matter (POM), with the increase in clam biomass, is larger than the corresponding reduction in chlorophyll. In fact, chlorophyll represents a small fraction of suspended organics (c.a. 10%), suggesting that bivalves depend mostly on suspended detritus for food in Ria Formosa.

Table 3-1 – Concentrations of several water quality variables (POM – Particulate organic matter; TPM – Total particulate matter) and *R. decussatus* biomass averaged over one month, for bivalve rearing areas (cf. – Fig. 2-2). Initial biomass densities were 1, 2 and 3 kg (fresh weight) m^{-2} for normal, double and triple densities, respectively.

	Ammonium **µmol L^{-1}**	**Oxygen** **mg L^{-1}**	**POM** **mg L^{-1}**	**TPM** **mg L^{-1}**	**Phytoplankton** **µg Chl L^{-1}**	***R. decussatus*** **kg (FW) m^{-2}**
Normal density	11.4	8.2	1.7	7.6	0.33	1.4
Double density	17.7	8.1	1.2	6.8	0.29	2.2
Triple density	24.7	7.9	1.0	6.2	0.27	3.0

3.1.2 Scenario set 2 – Use of salt-marsh areas

Although specific scenarios with and without salt marshes will not be presented here, their relative importance to lagoon biogeochemistry was apparent during the model calibration process (Duarte et al., 2006), when it became clear that there are important sinks of nitrogen (mostly nitrate) in Ria Formosa. Nitrate nitrogen riverine inputs are much larger than corresponding ammonium inputs. However, in the lagoon, ammonium nitrogen tends to be larger than nitrate nitrogen (Falcão, 1997). According to Falcão (unpublished), Ria Formosa salt marshes act as a nitrate sink and as an ammonium source. The biogeochemical model predicted higher ammonium than nitrate concentrations only when these salt marsh sink-source processes were considered. Furthermore, without considering these processes, lagoon nitrate and ammonium concentrations were much higher than observed (up to ten fold higher). In order to analyse properly this scenario set it will be necessary to gather more data to quantify the functional role of salt marshes in Ria Formosa.

3.1.3 Scenario set 2 –Population / Waste water treatment

Table 3-2 summarizes the results of the simulations described in 2.4.3. The results obtained suggest that average values for all variables included are reduced under summer river flows. This reduction is nearly 100% for nitrate with a poor influence of water column biogeochemical processes. The largest effect on nitrate is explained by its high concentrations in river water (values in excess of 500 μmol N L^{-1}). These high nitrate loads may probably be explained by intensive use of fertilizers at the extensive agricultural areas drained by the river network. However, the model predicts a rapid decline in nitrate concentrations with distance from river mouths (Fig. 3-2). It is noteworthy that ammonium concentrations practically double when TPM or nutrients are treated as non-conservative (Table 2-4, simulations 5 - 12), as a result of POM mineralization or denitrification, respectively. This doubling is much larger than the combined effect of river and WTP discharges. It is also relevant to see that WTP discharges seem to contribute more than river discharges for ammonium concentrations.

The results presented here are not in full accordance with the classification of Ria Formosa as "Coastal waters" by INAG (2005). The classification as "Transitional waters", implying a substantial influence by freshwater flows (EU, 2000), seem to apply when river discharges are relevant, namely, in winter months and in the case of nitrate.

Subtidal and intertidal areas of the lagoon are extensively covered by benthic macrophytes, such as macroalgae (*Enteromorpha* spp. and *Ulva* spp.), seagrasses (*Zostera* sp., *Cymodocea nodosa* and *Ruppia cirrhosa*) and *Spartina maritima* that dominate the low salt marshes (Falcão, 1997). The inter-tidal areas are mainly covered by *Spartina maritima* (8 km^2), seagrasses (8.2 km^2) and macroalgae mats (2.5 km^2) (Aníbal, 1998). From these vegetation cover values, annual production estimates and known Redfield ratios for the various taxonomic groups, nitrogen and phosphorus daily mean uptakes may be obtained. Regarding macroalgae, such estimates are reported in Serpa (2004). Concerning *Spartina maritima* and *Zostera noltii* (the dominant seagrass), production estimates are reported in Santos et al.

(2000), whereas nitrogen and phosphorus contents were taken from Valiela (1995). A similar approach was followed for phytoplankton, from primary production estimates reported in Duarte et al. (2003).

Results obtained are summarized in Table 3-3, together with daily river nitrogen and phosphorus discharges. It is noteworthy that the values presented are only approximate, since they do not take into account subtidal biomasses of benthic species, however, they seem to show that the contribution of river nutrient discharges to primary production, corresponds roughly to macroalgae nitrogen and phosphorus consumption. They also suggest that primary producers may be ordered by decreasing production rates and nutrient consumptions as phytoplankton, *Zostera noltii*, *Spartina maritima* and macroalgae. This contradicts results obtained by other authors in shallow coastal lagoons and bays, where macroalgae production dominates over phytoplankton (Sfriso et al., 1992; Valiela et al., 1992; McGlathery et al., 2001). The lower phytoplankton production has been attributed to nutrient competition between macroalgae and phytoplankton (Fong et al., 1993; Thybo-Christensen & Blackburn, 1993; McGlathery et al., 1997) and to water residence times shorter than phytoplankton duplication ratio (Valiela et al., 1997). This contradiction may be tentatively explained by:

(i) Benthic production does not seem to be macroalgae dominated in Ria Formosa, with rooted macrophytes playing an important role (Table 3-3). In fact, macroalgae tend to dominate as lagoons become eutrophic (Harlin, 1995), which is not the case of Ria Formosa.

(ii) Water residence time is longer than phytoplankton doubling time - phytoplankton cell doubling ratio in Ria Formosa is less than 2 days (Duarte et al., 2003) and it takes approximately 11 days for a 90% water exchange between the lagoon and the sea (see above).

Table 3-2 – Summary of simulations described in Table 2-4. All results are in μmol L^{-1} for nutrients and mg L^{-1} for TPM and POM (see text).

Simulation	Ammonium		Nitrate		Nitrite		Phosphate		TPM		POM	
	Average	Max	Average	Max	Average	Max	Average	Max	Average	Max	Average	Max
1	0.50	4.23	4.24	674.69	0.12	3.01	0.43	17.05	6.06	40.00	0.26	5.53
2	0.36	4.23	4.23	674.69	0.12	3.01	0.41	17.05	6.06	40.00	0.25	5.53
3	0.49	4.23	2.76	674.69	0.12	3.01	0.40	17.05	6.04	40.00	0.25	5.53
4	0.36	4.23	2.74	674.69	0.12	3.01	0.38	17.05	6.04	40.00	0.25	5.53
5	0.95	4.23	4.24	674.69	0.12	3.01	0.44	17.05	6.04	40.00	0.23	5.53
6	0.81	4.23	4.23	674.69	0.12	3.01	0.42	17.05	6.03	40.00	0.23	5.53
7	0.97	4.23	2.76	674.69	0.12	3.01	0.41	17.05	6.02	40.00	0.22	5.53
8	0.82	4.23	2.74	674.69	0.12	3.01	0.39	17.05	6.01	40.00	0.22	5.53
9	0.83	13.49	3.88	674.69	0.12	3.01	0.43	17.05	6.06	40.00	0.26	5.53
10	0.75	13.01	3.8	674.69	0.12	3.01	0.41	17.05	6.06	40.00	0.25	5.53
11	0.62	14.12	2.58	674.69	0.12	3.01	0.40	17.05	6.04	40.00	0.25	5.53
12	0.54	14.06	2.49	674.69	0.12	3.01	0.38	17.05	6.04	40.00	0.25	5.53

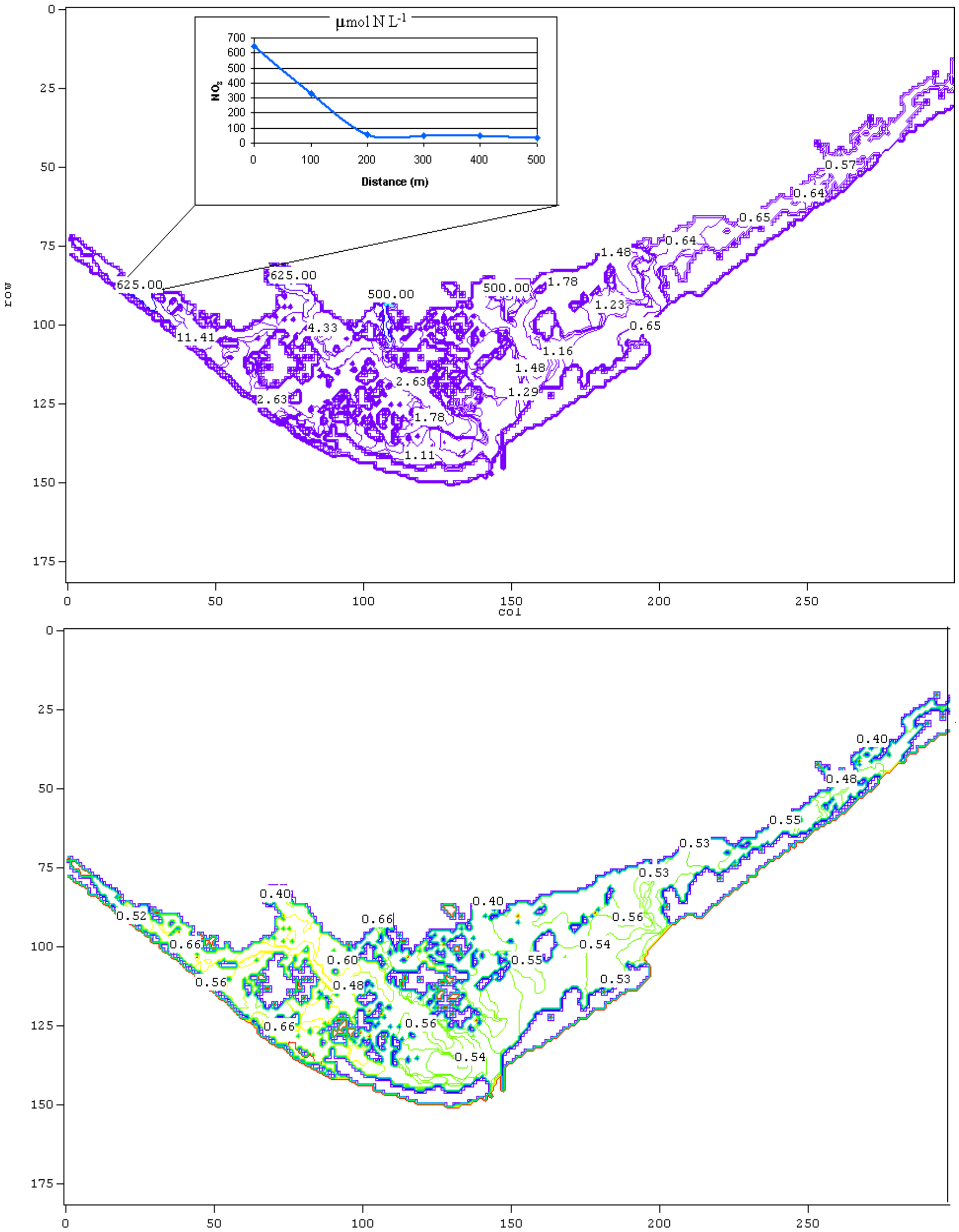

Fig. 3-2 – Nitrate concentration isolines predicted by the model after simulating a period of 15 days with river and WTP inflows (upper) and without inflows (lower). The plot inserted in the upper figure shows the decrease in nitrate concentration as a function of distance from river mouth, for one of the rivers. Numbers at both axes of the isoline plots refer to model grid line and column numbers (see text).

Table 3-3 – Estimates of nitrogen and phosphorus daily consumptions by main primary producers in Ria Formosa, from production figures and known Redfield ratios, and river discharges (see text).

	Nitrogen (kg d^{-1})	**Phosphorus (kg d^{-1})**
Spartina maritima	289 - 552	19 – 37
Zostera noltii	473 - 647	31 - 43
Macroalgae	189	27
Phytoplankton	546	76
River discharges	**187**	**13**

3.1.4 Scenario set 4 – Water circulation

The integration of flows across the inlets made possible to estimate their average input-output values for a period of a month. In Fig. 3-1, a synthesis of obtained results over the whole Ria shows that the Faro-Olhão inlet is by far the most important, followed by Armona, "new" and Fuzeta inlets. It is also apparent that the Faro-Olhão has a larger contribution as an inflow pathway, whereas the remaining ones contribute more as outflow pathways. The small difference between inflow and outflow total values do not imply any violation of volume conservation, but solely that during the period considered there was a net exchange of volume between the Ria and the sea. The results obtained suggest that part of the water that enters the Ria though the Faro-Olhão inlet is distributed west and eastwards, probably reducing the flood period in other areas. The results presented in Table 3-4 suggest that ebb period is larger than the flood period. This may result from ebb water taking more time to reach the ocean by outflowing only thought nearby inlets, whereas during the flood, there seems to be some volume redistribution among different inlets. Water residence time (considering a 90% washout) ranges from less than one day, near the inlets, to more than two weeks, at the inner areas, with an average value of 11 days.

The effects of several changes in lagoon bathymetry on current velocities at chosen points, water residence times and time integrated flows across the inlets are summarised in Tables 3-4 and 3-5. Obtained results show that channel deepening tends to increase water residence time, presumably due to the corresponding increase in lagoon volume, whereas sand accretion at the “Fortaleza Growing Area” has the opposite effect. There are some exceptions, but these correspond to less than 1% changes in water residence times. The “Fuseta Channel” scenario (Fig. 2-5) exhibits the largest outflow reduction across the “New” and the “Fuzeta” inlets. This may be viewed as a negative impact, since outflow reduction may increase sand accumulation within the lagoon. These trends suggest that bathymetric changes in one side of the lagoon may have impacts tens of km away.

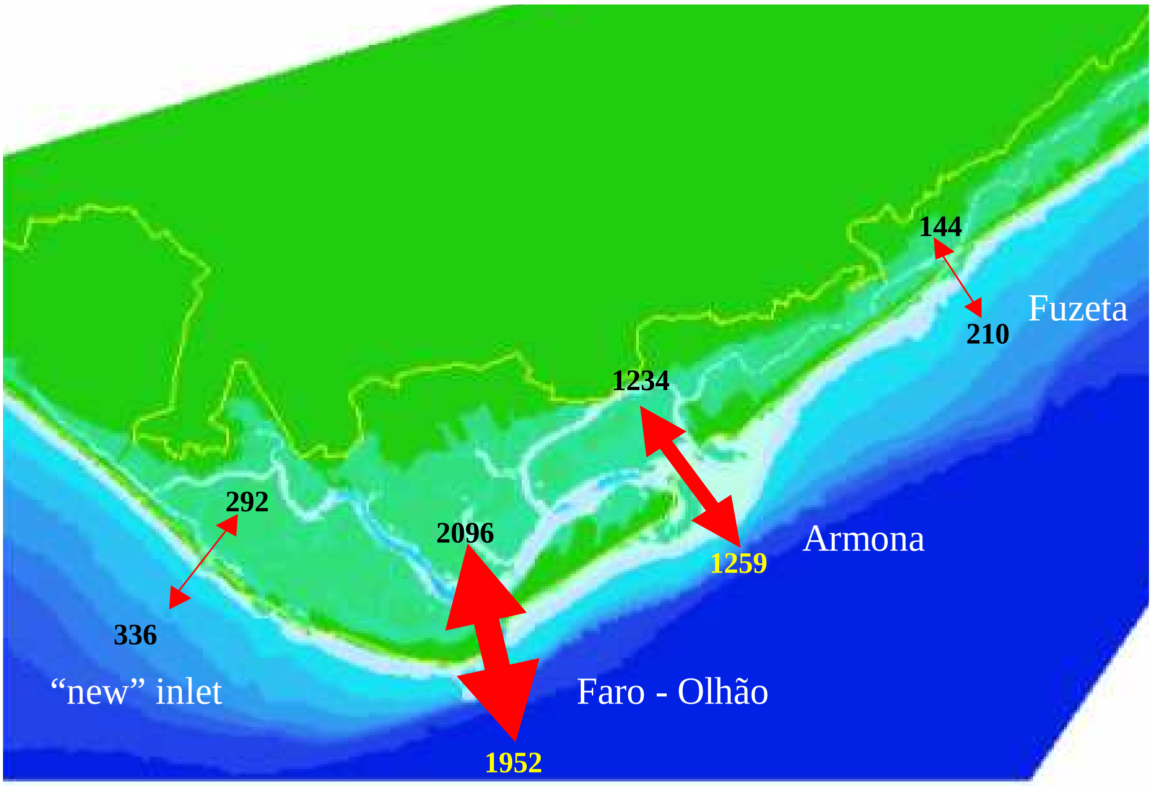

Fig. 3-1– Averaged inflows and outflows ($m^3 s^{-1}$) through Ria Formosa inlets (see text).

Table 3-4 – Predicted average ebb and flood current velocities and periods at the current meter stations depicted in Fig. 1 for the “Western” Ria Formosa (see text).

Station	Ebb		Flood	
	Average current velocity (cm s^{-1})	**Period (h)**	**Average current velocity (cm s^{-1})**	**Period (h)**
Ancão	17.90	7.16	24.57	5.20
Faro-Harbour	50.69	6.10	39.49	6.06
Olhão-Canal de Marim	32.30	6.72	31.07	5.47
Fuzeta-Canal	28.49	6.25	37.92	4.94

Table 3-5 – Summary of 50, 90 and 99% water residence time, inflow and outflow changes in relation to the standard scenario (see text).

Scenarios	**Variations (%)**					
	Residence Times			**Flows**		
	50% RT	**90% RT**	**99% RT**	**Inlets**	**Inflows**	**Outflows**
Ramalhete Channel	1.6	10.0	6.0	"New Inlet"	64.0	-5.3
				Faro-Olhão	8.6	19.5
				Armona	12.4	10.2
				Fuseta	-12.4	20.4
Faro-Olhão Inlet	24.4	28.7	13.9	"New Inlet"	64.0	-8.5
				Faro-Olhão	-1.9	11.6
				Armona	2.8	7.5
				Fuseta	-18.0	13.1
Olhão Channel	-0.3	0.6	0.1	"New Inlet"	75.8	-3.5
				Faro-Olhão	9.7	18.2
				Armona	7.3	7.6
				Fuseta	-8.7	17.0
Fuseta Channel	44.2	75.1	26.4	"New Inlet"	72.8	-3.2
				Faro-Olhão	8.3	16.4
				Armona	12.1	10.5
				Fuseta	-46.9	-22.6
Fortaleza Growing Area	-1.5	-1.4	-2.0	"New Inlet"	77.5	-5.9
				Faro-Olhão	8.1	15.9
				Armona	10.7	8.4
				Fuseta	-10.6	19.3

Tables 3-6 and 3-7 summarize time and space integrated results obtained with the biogeochemical simulations for several water column, pore water and sediment variables, regarding the standard simulation and two of the dredging scenarios – “Olhão channel and “Ramalhete channel”. Obtained results suggest that both scenarios lead to a decrease in water column and pore water nutrient concentrations – mostly ammonium and nitrate. There is also an important decrease in sediment organic matter for the “Ramalhete channel”scenario.

As mentioned before, both scenarios lead to a slight increase in water residence residence time. Therefore, the decrease in nutrient concentrations probably results from an increase in exchanges with the sea over the dredged areas. The ammonium reduction may be viewed as an improvement in water quality, according to the IFREMER classification scheme (Austoni et al., 2004).

Table 3-6 – Average values for eight water columns variables integrated over a period of one year for the three Standard simulation, the Olhão Channel simulation and the Ramalhete Channel simulation (cf. – Methodology – Scenario analysis).

Variables		**Standard simulation**	**Olhão Channel**	**Ramalhete Channel**
Ammonium		8.58	7.44	5.08
Nitrate	μmol L^{-1}	8.18	4.23	3.58
Nitrite		0.03	0.01	0.07
Phosphate		0.90	0.76	0.53
Oxygen		8.28	8.29	8.33
POM	mg L^{-1}	2.70	2.67	3.80
TPM		13.34	12.76	13.08
Phytoplankton	μg Chl L^{-1}	0.40	0.40	0.43

Table 3-7 – Average values for eight sediment and pore water variables integrate over a period of one year for the three Standard simulation, the Olhão Channel simulation and the Ramalhete Channel (cf. – Methodology – Scenario analysis).

Variables		**Standard simulation**	**Olhão Channel**	**Ramalhete Channel**
C Organic		4105.89	4108.78	4156.31
N Organic	μg g^{-1}	215.59	215.16	199.14
P Organic		51.62	51.16	46.74
P Adsorbed		5.63	5.47	4.43
NH_4 In Pore Water		22.34	21.02	21.20
NO_3 In Pore Water	μmol L^{-1}	7.74	4.01	2.63
PO_4 In Pore Water		2.86	2.78	2.31
O_2 In Pore Water	mg L^{-1}	0.61	0.61	0.42

4 Conclusions

The results presented and discussed regarding the various management scenarios analysed so far suggest that increasing bivalve densities in rearing areas may lead to a relatively important decline in water quality and bivalve growth. Apparently, WTP contribution is mainly though ammonium discharges, although riverine nitrate-nitrogen inputs are much larger. Although bacterial contamination was not yet analysed in the present work, it should be included in future scenario analysis. A bacterial object will be included in EcoDynamo to allow such analysis. The results presented are not in full accordance with the classification of Ria Formosa as “Coastal waters” by INAG (2005). The classification as “Transitional waters”, (EU, 2000), seem to apply here, considering the influence of river discharges, namely, in winter months and in the case of nitrate. The suggested changes in lagoon bathymetry, tend to increase water residence time and may produce hydrodynamic effects (e.g. changes in inlet residual flows) at tens of km away. Dredging operations is two of the main navigation channels (Olhão and Ramalhete) may have a positive impact on water and sediment quality by inducing reductions in water column and sediment pore water nutrients, as well as on sediment organic contents.

Future improvements in the model and corresponding scenario analysis should include the effects of bacterial contamination (as mentioned above) and improvements in the way sediment deposition and resuspension are simulated. Ideally, the model should be able to anticipate the consequences of several scenarios on inlet changes and corresponding feedbacks to hydrodynamics and biogeochemistry.

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