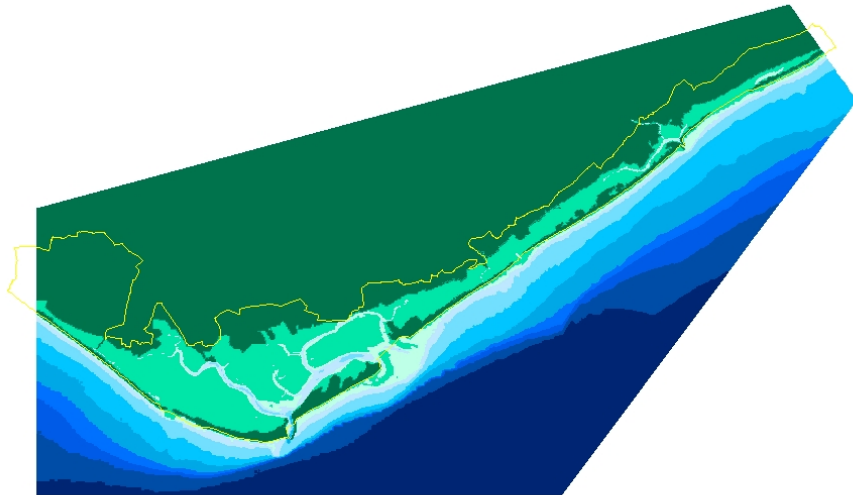


**Development of an Information Technology Tool for the
Management of European Southern Lagoons under the
influence of river-basin runoff**

EVK3-CT-20022-00084 (DITTY Project)

**DELIVERABLE D3 : SYNTHESIS REPORT
(September 2003) RIA FORMOSA**



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1 SITE DESCRIPTION

1.1 Geography, geomorphology, hydrology and morphometry of the site

The 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 the slope the inter-tidal area is exposed to the atmosphere for several hours over each semi-diurnal tidal period. Fresh water input to the lagoon is negligible and salinity remains close to 36 ppt, except during sporadic and short periods of winter run-off. The tidal amplitude varies from 1 to 3.5 meters and the mean water depth is 3.5 m. There is a rather intense exchange of 40 – 70% of water mass during each tide.

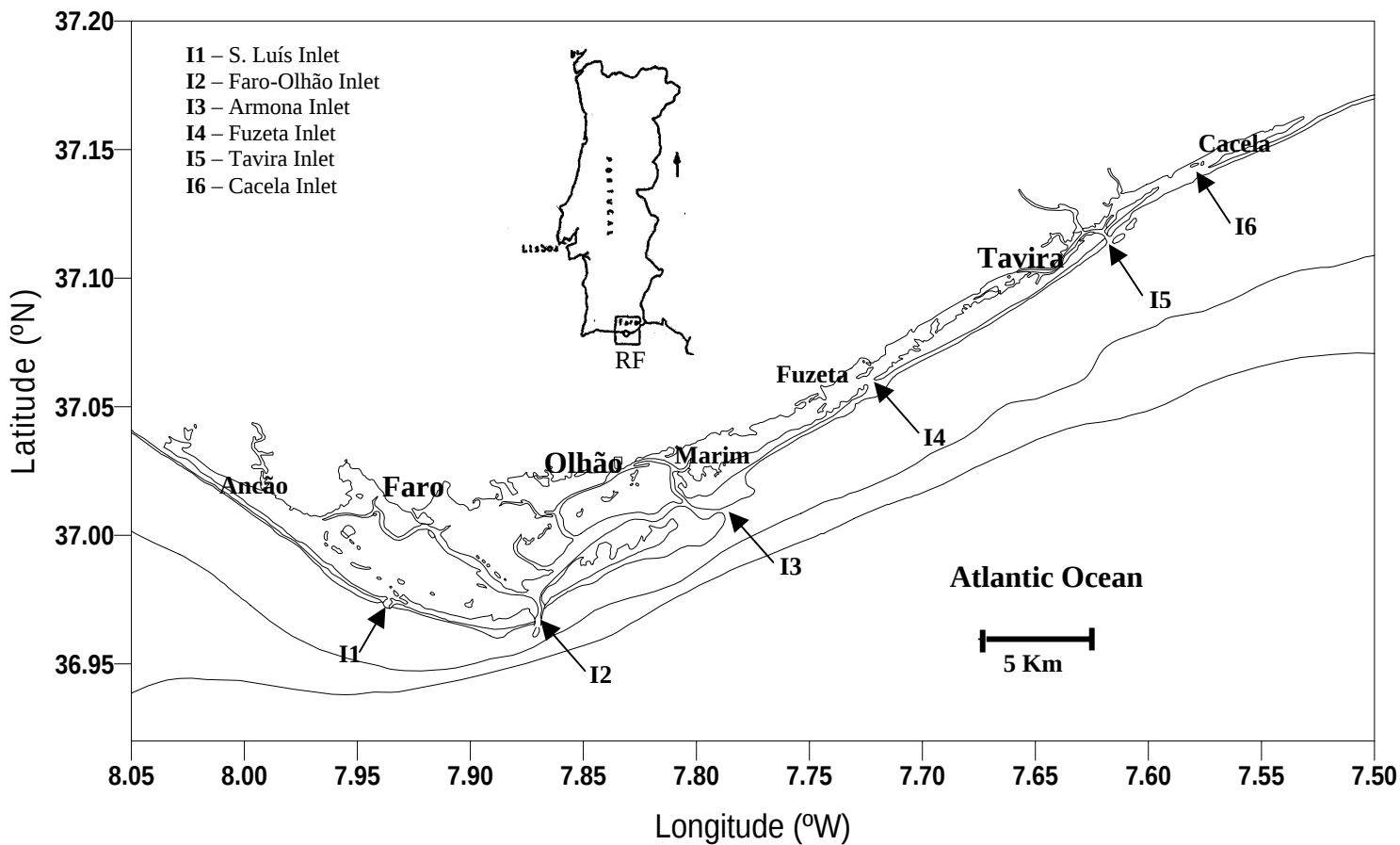


Figure 1-1- Geographic location of Ria Formosa and its inlets.

2 CATCHMENT

2.1 Hydrographic Network

The Ria Formosa is located in the southernmost part of Portugal (Sotavento region) whose limit is the Guadiana hydrographic basin. The origin of its rivers is mostly in the Caldeirão Mountain and its watercourses drain perpendicular to the South in the direction of the Atlantic Ocean. Most rivers are ephemeral with no runoff or very reduced runoff during part of the year, between June and October. The most important watercourses in the Ria Formosa basin are river Gilão and streams Alportel, S. Lourenço, Zambujosa, Seco and Cacela (Fig. 2-1). River Gilão and streams Almargem and Seco, cover almost half of the whole catchment area. Their characteristics are presented in Table 2-1. The Ria Formosa basin has an area of 864.26 km², a perimeter of 165.989 km, and a maximum altitude of 522 m (MAOT, 2000a).

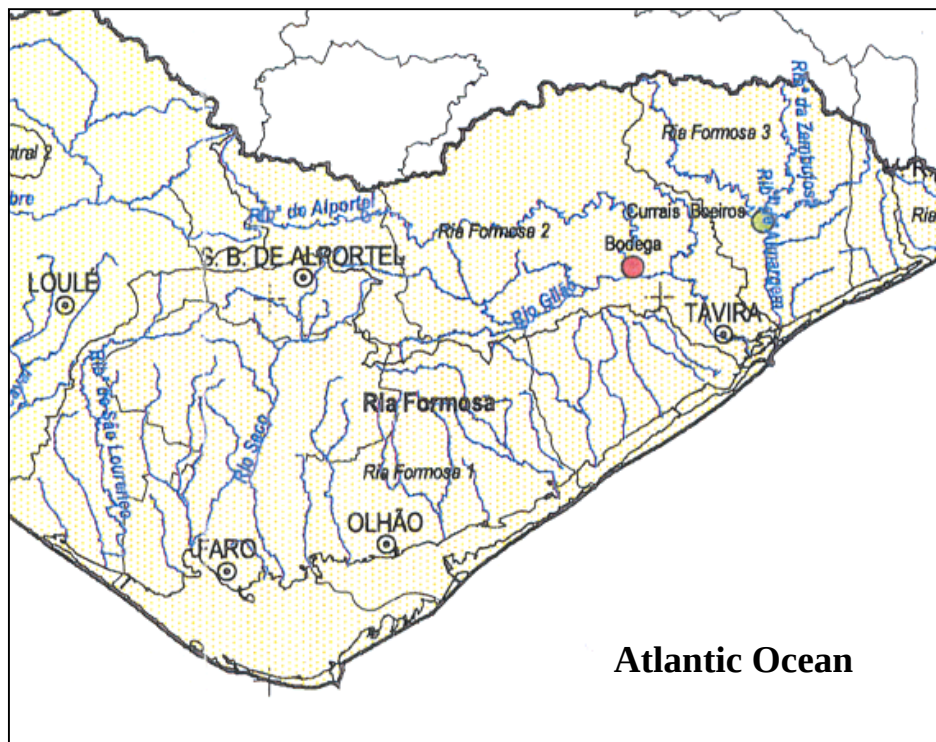


Figure 2-1- The Ria Formosa watershed and its hydrographic network.

Table 2-1 –Characteristics of the most important watercourses of Ria Formosa watershed (MAOT, 2000b).

	Length (km)	Max altitude (m)	Min altitude (m)	Δh (m)	Average slope (%)	Total discharge (annual mean) (m ³ year ⁻¹)
Gilão	32.740	326	0	326	1.0	77 X 10 ³
Almargem	49.450	453	16	437	0.9	36 X 10 ³
S. Lourenço	24.656	340	0	340	1.4	18 X 10 ³
Zambujosa	21.904	334	0	334	1.5	-
Seco	21.315	310	0.8	309	1.5	41 X 10 ³
Cacela	6.367	119	0	119	1.9	2.4 X 10 ³

In the Algarve region (south-western part of the Iberian peninsula), the climate is strongly influenced by atmospheric circulation and topography.

The monthly and annual data suggest an irregularity of the annual precipitation in the basin (from 600 to 800 mm). Generally the most wet month of the year is December with about 17% of total annual precipitation, followed by November and January (about 15%). The driest months are July and August with less than 1% of annual precipitation.

The maximum mean annual temperature was recorded in Tavira (≈ 18.3 °C). In this zone temperature reaches values of 25.8°C in August and the mean annual evapotranspiration is about 882 mm. From April to September actual evapotranspiration is higher than precipitation, especially in May, and the mean values range from 50 to 60 mm depending on the water availability in the soil.

During spring, summer and beginning of autumn, the winds blow predominantly from Southeast in this part of the Algarve. The wind speed is about 30 to 40 km/h in the morning, decreasing during the afternoon.

2.2 Agricultural land use

The area permanently used for agriculture in the Ria Formosa watershed is about 19% corresponding to 16 500 ha from which 300 ha are occupied by vegetable gardens (Fig. 2-2). The cereals, vegetables, potatoes, fresh fruits, citrinous, dry fruits, vine and olive are the most typical crops practiced in agricultural areas (<http://www.ccr-alg.pt>). In the east side of the watershed, predominate the dry fruits, olive and vine crops whereas in the west side, horticulture and fruit culture are practiced mainly in greenhouses (Fig. 2-2). An important proportion of the watershed (17%) is available for cultivation.

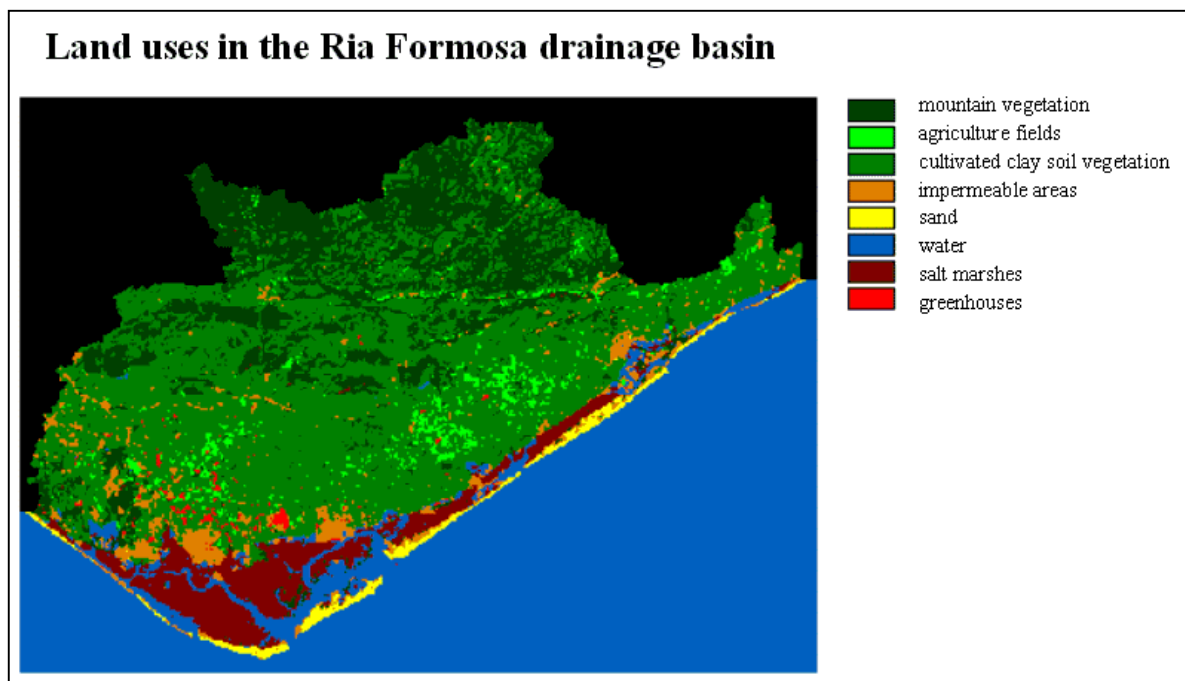


Figure 2-2 - Land uses in the Ria Formosa drainage basin.

(Source: Project OARRE. EU contract EVK3-CT1999-00002)

2.3 Water quality

2.3.1 Aquiferous

Data obtained from a monitoring program carried out over 2000, 2001 and 2002, in different aquiferous (Almancil, Campina de Faro, S. Brás de Alportel, Quelfes and Tavira) of the Ria Formosa watershed (Fig. 2-3) are presented in table 2-2. Table 2-3 shows the Maximum Recommended Value (MRV) and the Maximum Admissible Value (MAV) for nitrates and chlorides (DRAOT- 2003 “Plano de Bacia Hidrográfica das Ribeiras do Algarve”).

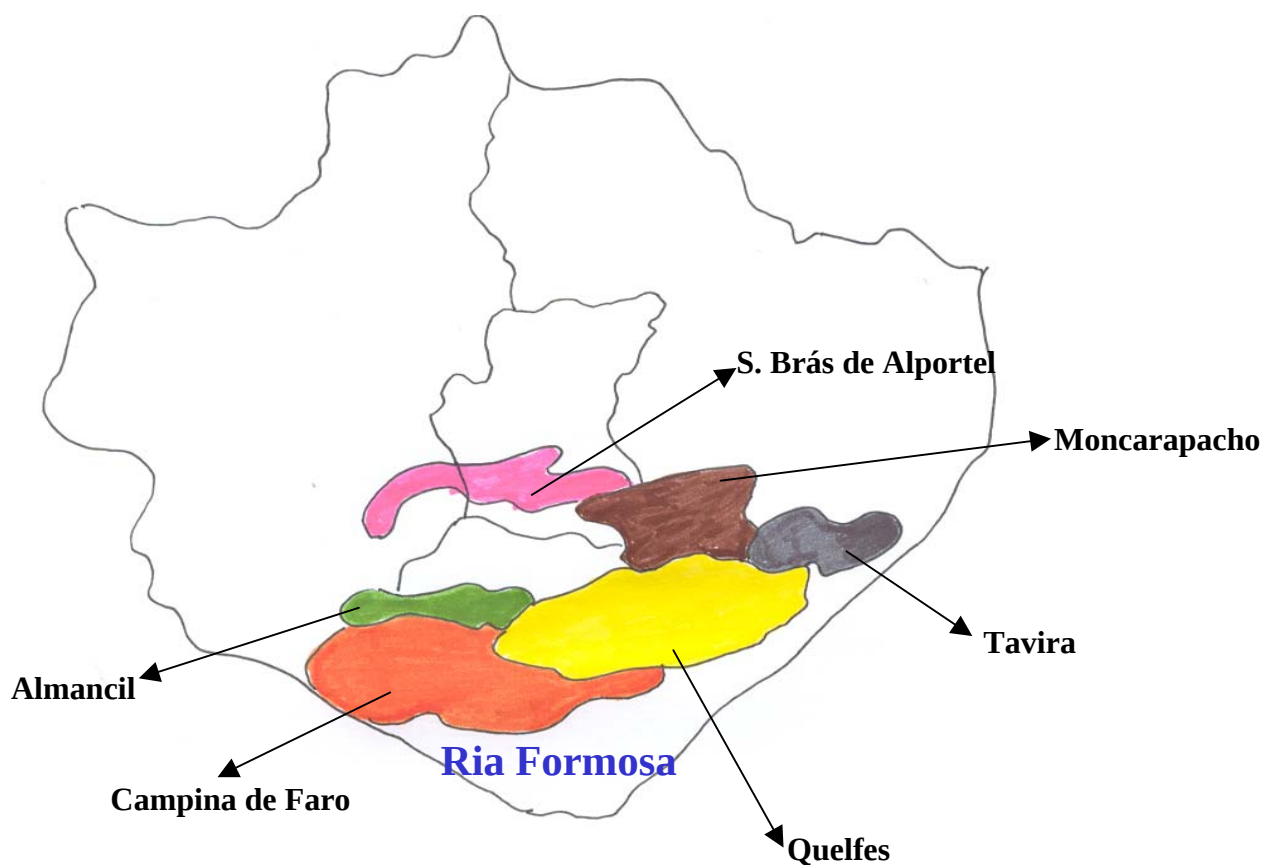


Figure 2-3 - Different aquiferous in the Ria Formosa watershed.
(DRAOT- 2003 “Plano de Bacia Hidrográfica das Ribeiras do Algarve”)

Table 2-2 – Mean annual values of nitrates and chlorides concentrations in different aquiferous of the Ria Formosa watershed.

	Almancil			Campina de Faro			S.Brás Alportel			Quelfes			Tavira		
	2000	2001	2002	2000	2001	2002	2000	2001	2002	2000	2001	2002	2000	2001	2002
NO ₃ ⁻ (10 ³ mmol m ⁻³)	0.73	0.71	0.73	14.3	19.4	17.4	1.4	1.25	1.4	8.5	5.7	4.3	3.14	4.22	5.3
Cl ⁻ (10 ³ mmol m ⁻³)	1.4	1.35	1.5	4.2	5.6	5.2	1.05	1.03	0.9	3.35	2.9	2.3	2.05	2.25	2.31

Table 2-3 - Maximum Recommended Value (MRV) and Maximum Admissible Value (MAV) for nitrates and chlorides.

(Source: DRAOT- 2003 “Plano de Bacia Hidrográfica das Ribeiras do Algarve”)

NO ₃ ⁻		Cl ⁻	
10 ³ mmol m ⁻³		10 ³ mmol m ⁻³	
MRV	MAV	MRV	MAV
1.8	3.6	5.6	-

The mean annual values shown in table 2-2 reveal that the Campina de Faro aquiferous located in the western part of the lagoon reach the highest nitrate levels. These values are one order of magnitude higher than the MRV (Table 2-3). The agricultural activity practiced in the area of Almancil aquiferous is reduced if we compare with the Campina de Faro. Further, this aquiferous occupies a restricted area (»1/3 Campina area) thus, explaining the lowest values of nitrates found in Almancil. Aquiferous located in the east side of the lagoon, where agricultural activity is extensive (dry fruits, olive, vine) also present lower levels of nitrates, close to the MRV. These points to the use of more fertilizers in the intensive cultures (horticulture and fruits in greenhouses) practiced in the area of Campina de Faro aquiferous. The extent of land used for agriculture in the east side of the lagoon is about one order of magnitude higher than that of the west side (<http://www.ccr-alg.pt>). This reinforce that extensive cultures (east side) are less damaging regarding aquiferous pollution, than the intensive cultures practiced in the west side, in a more restricted area.

In the monitored aquiferous, mean values of chlorides are lower than the MRV suggesting that salt intrusion does not occur in the aquiferous of Ria Formosa watershed.

2.1.2 Surface flows

The data concerning surface waters (DO-dissolved oxygen, BOD₅-biochemical oxygen demand, COD-chemical oxygen demand, faecal coliforms, NO₃⁻, PO₄⁻³, and TON-total organic nitrogen), obtained from a monitoring program carried out in 2002, are presented in table 2-4 (for River Gilão, crossing the east side of the lagoon watershed) and in table 2-5 (for Stream Seco, crossing the west side).

The values of DO, BOD₅, COD and TON obtained in River Gilão and Stream Seco correspond to the expected for superficial waters without great pollution constraints (Falcão *et al.*, 1991). However the values of nitrates, phosphates and faecal coliforms were clearly higher in Stream Seco waters. In this stream, the studied parameters reach values one order of magnitude higher than those obtained for River Gilão. These findings may be due to the practice of intensive agriculture (excess of fertilizers) and higher population density in the west side of the watershed (sporadic inputs of domestic sewage).

Table 2-4 - Values of dissolved oxygen (DO), biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), faecal coliforms (Faecal Col.), nitrates (NO₃⁻), phosphates (PO₄⁻³) and total organic nitrogen (TON). Source: DRAOT Bulletin (Monitoring program performed in River Gilão).

River Gilão								
	DO %	BOD5 mol O ₂ m ⁻³	COD mol O ₂ m ⁻³	Tot. Col. PN/ml	Faecal Col. PN/ml	NO ₃ ⁻ mmol m ⁻³	PO ₄ ⁻³ mmol m ⁻³	TON mmol m ⁻³
Jan	104.0	0.063	0.156	15.00	0.43	137.0	12.1	74.0
Febr	99.0	0.063	0.156	4.60	0.43	21.4	1.4	72.0
Mar	106.0	0.063	0.156	7.50	0.01	34.0	1.9	70.0
Apr	119.0	0.063	0.156	24.00	1.50	125.0	1.1	68.0
May	113.0	0.063	0.156	110.00	0.75	21.4	2.2	64.0
Jun								
Jul	103.0	0.041	0.256	2.30	0.04	14.0	1.1	72.0
Aug								
Sep	108.0	0.041	0.306	2.30	0.90	6.0	0.5	63.0
Oct	97.0	0.063	0.438	110.00	46.00	107.1	1.2	62.0
Nov	109.0	0.063	0.156	24.00	0.23	14.3	1.1	58.0
Dec	103.0	0.063	0.156	9.30	0.10	14.3	1.5	64.0

Table 2-5 - Values of dissolved oxygen (DO), biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), faecal coliforms (Faecal Col.), nitrates (NO₃⁻), phosphates (PO₄⁻³) and total organic nitrogen (TON). Source: DRAOT Bulletin (monitoring program performed in stream Seco)

Stream Seco								
	DO %	BOD5 mol O ₂ m ⁻³	COD mol O ₂ m ⁻³	Tot. Col. PN/ml	Faecal Col. PN/ml	NO3 mmol m ⁻³	PO4 mmol m ⁻³	TON mmol m ⁻³
Jan	120	0.063	0.156	110.0	11.0	564.3	12.3	73,0
Febr	133	0.063	0.156	110.0	4.6	614.3	12.1	61,0
Mar	143	0.063	0.219	230.0	4.6	914.3	33.7	55,0
Apr	126	0.063	0.156	430.0	11.0	585.7	23.7	58.0
May	162	0.063	0.188	110.0	0.4	200.0	26.5	50.0
Jun	128	0.094	0.156	460.0	2.4	564.3	7.2	65.0
Jul								
Aug								
Sep	82	0.063	0.281	234.0	4.2	578.6	28.9	77.0
Oct	109	0.063	0.022	256.0	4.7	657.8	13.5	61.6
Nov	116	0.063	0.214	117.0	5.2	885.4	17.6	75.4
Dec	111	0.063	0.188	110.0	11.0	1228.6	40.0	85.0

3 COASTAL AQUATIC ECOSYSTEM

The Ria Formosa and some of its hinterland has been included in a Natural Park (18 400 ha) and accepted as a Natura 2000 network and a Ramsar site, due to the recognition of its environmental importance. The Ria is a shallow meso-tidal lagoon, located along the eastern part of the south coast of Portugal, with an extension of 55 km (from Ancão to Cacela), a maximum width of 6 km and with a wet area of 10 500 ha (Fig. 1-1). The lagoon is protected from the ocean by a sandy barrier island interrupted by six inlets (S.Luís, Faro-Olhão, Armona, Fuzeta, Tavira e Cacela). Tidal movement and water exchanges between the lagoon and the ocean (through the inlets) determine the system evolution (Neves, 1992).

Several sporadic streams drain the watershed during rainfall period and one river (Gilão) supplies freshwater to the lagoon over the year. Salinity remains close to 36 ppt, except during sporadic and short periods of winter run-off (Falcão, 1997). This ecosystem is considered a nursery for a large number of coastal species (Monteiro, 1989), and its extensive inter-tidal areas (5 300 ha) are

used as growth bank of clams (500 ha), fish farms (460 ha) and salt ponds (1130 ha) (Bulletin of Ria Formosa Natural Park). The tidal amplitude varies from 1 to 3.5 meters meaning that a rather intense exchange of water mass (40 to 70%) occurs during each tide (Sprung, 1994) and large inter-tidal areas are exposed to the atmosphere for several hours over each semi-diurnal tidal period. The natural biogeochemical cycles of this lagoon are essentially regulated by tidal exchanges with the seawater and by the exchanges with the sediment interface.

The morphological diversity of this ecosystem determines different environmental units according to morphological and phytomorphological criterions (Bulletin of Ria Formosa Natural Park). These environmental units are classified as:

Tidal flats establish the connection between salt marshes and tidal channels. These areas are characterized by silt-clay or muddy-sand inter-tidal bottoms without halophyte vegetation but abundantly covered by the seagrass *Zostera noltii*. Approximately 500 ha of the tidal flats are used for extensive clam cultivation, which implies removal of the vegetation and a periodical addition of sand.

Salt marshes are located above tidal flats. Silt-clay sediments colonised by halophyte species characterize these areas. The vegetation is dominated by *Spartina maritima*, *Salicornia nitens*, *Arthrocnemum perenne*, *Suaeda maritima* and *Atriplex portucaloides*. The low salt marsh is almost exclusively colonized by *Spartina maritima* and the bigger plants colonize the high salt marsh with a shorter period of immersion.

Tidal channels allow an easy circulation of water. The bottom grain size varies from gross sand to fine fraction. Large areas of the bottom are covered by *Zostera marina*, which contributes to sedimentation of suspended particulate matter.

Lagoon beaches with sand and muddy-sand sediments appear especially within tidal flats and salt marshes.

3.1 Hidrography

As the volume of water exchanged between lagoon and sea varies from 30×10^6 to $100 \times 10^6 \text{ m}^3$, according to the tidal amplitude (CEPASA, 1980) and the sub-tidal water volume is $50 \times 10^6 \text{ m}^3$, we may assume that at neap and spring tide, 40% and 70% of the water volume are respectively exchanged with the sea, as referred by Sprung (1994). In the main channels, the speed of the current is below 1 m s^{-1} , while in the inlets it may overcome 2 m s^{-1} (Lima & Vale, 1980). The inputs of fresh water to the system are not significant, except from the river Gilão. Thus, the salinity of the lagoon water varies between 35.5 ppt to 36.6 ppt, except for periods of intense rainfall that may reach 30 ppt (Falcão *et al.*, 1992).

3.2 Water quality

The annual ranges of values from water quality parameters are presented in the tables 3-1, 3-2 and 3-3 (Falcão, 1997; Monitoring Program IPIMAR/CRIPSul). Table 3-1 presents the annual values of ammonium (NH_4^+), nitrates (NO_3^-), urea ($\text{CO}(\text{NH}_2)_2$), total nitrogen (TN), phosphates (PO_4^{3-}), total phosphorus (TP), silicates (SiO_2), chlorophyll *a* (Chl *a*), phaeopigments (Phaeop) and dissolved oxygen (DO) in the adjacent coastal water. Table 3-2, present the values of NH_4^+ , NO_3^- , $\text{CO}(\text{NH}_2)_2$, TN, PO_4^{3-} , TP, SiO_2 , Chl *a*, Phaeop and DO concentrations in the main channels of the lagoon, at low (LT) and high tide (HT) of spring tide. Table 3-3 show the values of NH_4^+ , NO_3^- , $\text{CO}(\text{NH}_2)_2$, TN, PO_4^{3-} , TP, SiO_2 , Chl *a*, Phaeop and DO in lagoon areas under direct impact of untreated wastewater discharges (Faro-Olhão), at low (LT) and high tide (HT) of spring tide.

Table 3-1 Range of annual values of ammonium (NH_4^+), nitrates (NO_3^-), urea ($\text{CO}(\text{NH}_2)_2$), total nitrogen (TN), phosphates (PO_4^{3-}), total phosphorus (TP), silicates (SiO_2), chlorophyll *a* (Chl *a*), phaeopigments (Phaeop) and dissolved oxygen (DO) in the adjacent coastal area.

NH_4^+	NO_3^-	TN	$\text{CO}(\text{NH}_2)_2$	PO_4^{3-}	TP	SiO_2	Chl <i>a</i>	Phaeop	DO
μM	μM	μM	μM	μM	μM	μM	$\mu\text{g L}^{-1}$	$\mu\text{g L}^{-1}$	mg L^{-1}
0.05 – 3.0	0.1 – 9.5	11.0 – 44.0	0.05 – 2.0	0.02 – 1.6	0.3 – 4.5	0.1 – 5	0.2 – 3.2	0.02 – 1.5	7.5 – 9.5

Table 3-2 - Range of annual values of ammonium (NH_4^+), nitrates (NO_3^-), urea ($\text{CO}(\text{NH}_2)_2$), total nitrogen (TN), phosphates (PO_4^{3-}), total phosphorus (TP), silicates (SiO_2), chlorophyll *a* (Chl *a*), phaeopigments (Phaeop) and dissolved oxygen (DO) in the main channels of the lagoon, at low (LT) and high tide (HT) of spring tide.

	NH_4^+	NO_3^-	Nt	$\text{CO}(\text{NH}_2)_2$	PO_4^{3-}	Pt	SiO_2	Chl <i>a</i>	Phaeop	DO
	μM	μM	μM	μM	μM	μM	μM	$\mu\text{g L}^{-1}$	$\mu\text{g L}^{-1}$	mg L^{-1}
HT	0.3 – 3.0	0.2 – 11.5	12.0 - 43.0	0.05 – 1.6	0.05 – 2.0	0.6 – 1.6	0.2 – 6.0	0.3 – 3.5	0.2 – 2.0	6.0 – 10.0
LT	0.8 – 4.0	0.05 – 5.9	10.0 - 25.0	0.2 - 3.0	0.05 – 3.6	0.9 - 2.5	0.6 - 14.0	0.2 - 6.0	0.1 - 3.0	5.0 - 11.0

Table 3-3 - Range of concentrations of ammonium (NH_4^+), total nitrogen (TN), urea ($\text{CO}(\text{NH}_2)_2$), phosphates (PO_4^{3-}), total phosphorus (TP), and dissolved oxygen (DO) in lagoon areas under direct impact of untreated wastewater discharges (Faro-Olhão), at low (LT) and high tide (HT) of spring tide. Source: Monitoring program IPIMAR/CRIPSul

	NH_4^+	Nt	$\text{CO}(\text{NH}_2)_2$	PO_4^{3-}	Pt	DO
	μM	μM	μM	μM	μM	mg L^{-1}
HT	300 - 600	42 – 197	1.0 – 8.0	2.0 – 75	3.0 – 29.0	5.0 – 7.2
LT	750 - 3000	79 – 680	16 – 108	24 – 147	62 - 152	1.0 – 4.0

The wide ranges of parameters found in water reflect the importance of the seasonal, spatial and tidal variability in this ecosystem. In the adjacent coastal water, the concentrations of NO_3^- , $\text{CO}(\text{NH}_2)_2$, NT and SiO_2 reach the highest values in winter while, in summer, NH_4^+ reach its peak. DO remains above 100% saturation (Falcão, 1997).

The DO concentrations in lagoon water remain close to saturation values over the year. The concentrations of SiO_2 , PO_4^{3-} , $\text{CO}(\text{NH}_2)_2$, Pt and Chl *a* at low tide exceeded largely the values recorded at high tide. This reflects the dilution effect caused by incoming seawater. An opposite

pattern was observed for NO_3^- and TN that present the higher values at high tide. In fact, these forms of nitrogen are imported from the sea, mainly during the period of lower water temperature (Falcão, 1997).

The water quality parameters for areas under direct impact of untreated wastewaters (Table 3-3) evidence eutrophication, confined to those areas close to the main urban centres. The high levels of organic and inorganic compounds of nitrogen and phosphorus associated with low levels of oxygen, weak renovation of lagoon water (neap tides) and high temperatures (summer), may originate environmental disturbances (chemical and biological) harmful for shellfish cultures.

3.3 *Sediment and sediment water interactions*

Sediment

The results of grain size analysis of sub-tidal and inter-tidal superficial sediments are presented in table 3-4. Near the inlets and in the main channels of the lagoon submitted to strong currents, prevail the sandy sediments while in the inner parts of the lagoon and inter-tidal areas, mud or muddy-sand sediments predominate (Granja, 1984; Monteiro, 1989).

Table 3-4 – Mean annual values of grain size and calcimetric analysis of superficial sediments in stations located near the inlets / main channels and inner parts of lagoon / inter-tidal areas.

Source: Monteiro, 1989

Stations	Clay (%)		Silt (%)		Sand (%)		CaCO ₃ (%)	
	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
Inlets / Main channels	0.55	0.39	0.78	0.42	95.58	7.45	5.02	2.34
Inner parts of lagoon / Inter-tidal areas	6.18	3.70	32.63	16.21	62.10	15.58	7.00	3.26

Sediment-water interactions

In this shallow lagoon, the influence of the bottom is of most importance on the regeneration of nutrients that enrich the water column (Lerat *et al.*, 1990; Kristensen, 1993; Forja *et al.*, 1994). Ammonium and phosphates levels were higher in pore waters of muddy sediments than in sandy sediments, which means that exchanges by molecular diffusion in areas which bottom is essentially constituted by sand, are less important than in muddy sediment areas (Falcão & Vale, 1998). The lower concentrations of ammonium and phosphates in pore water of sandy sediment may be attributed to the low quantity of organic matter accumulated in these areas and, possibly, to a more efficient renewal of pore water containing the products of organic matter decomposition (Shum & Sundby, 1996). As found in other environments (Nowicki & Nixon, 1985; Forja *et al.*, 1994), the calculated transport of ammonium by molecular diffusion was one-two orders of magnitude higher than that of phosphate, which means that ammonium is more available to the phytoplanktonic biomass. These findings corroborate other studies developed over the year in Ria Formosa in which ammonium benthic fluxes were also one-two orders of magnitude higher than phosphate fluxes (Fig. 3-1). The present values evidence that molecular diffusion in muddy sediments varies seasonally reaching the minimum in winter and the a peak in summer as occurs in other environments due to the intensive anaerobic decomposition of organic matter (Forja *et al.*, 1994).

The seasonal variations of nutrient benthic fluxes occurred together with changes on the N/P stoichiometry (Forja *et al.*, 1994). In fact, the N/P ratios in Ria Formosa (Fig. 3-2) were higher during the autumn/winter period probably due to the weaker transport of phosphorus across the sediment-water interface as described above. Phosphorus is accumulated in solid phase (adsorbed onto iron oxides) during winter, released to pore water and transferred to the overlying water in periods of higher temperature (Ohtake *et al.*, 1984; Kennedy *et al.*, 1984).

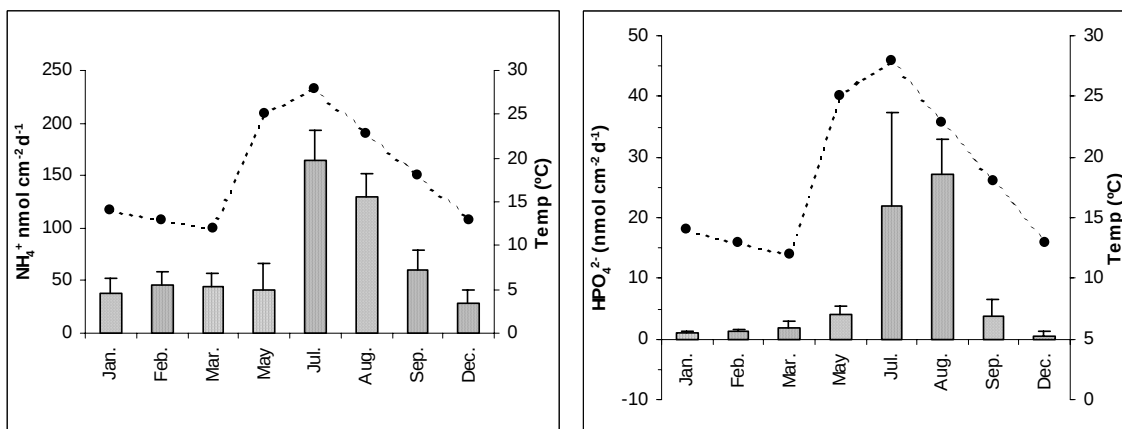


Figure 3-1 - Transport of ammonium and phosphate ($\text{nmol cm}^{-2} \text{d}^{-1}$) by molecular diffusion in muddy sediments with the mean monthly temperature of surface sediments.

Source: Falcão & Vale (1998)

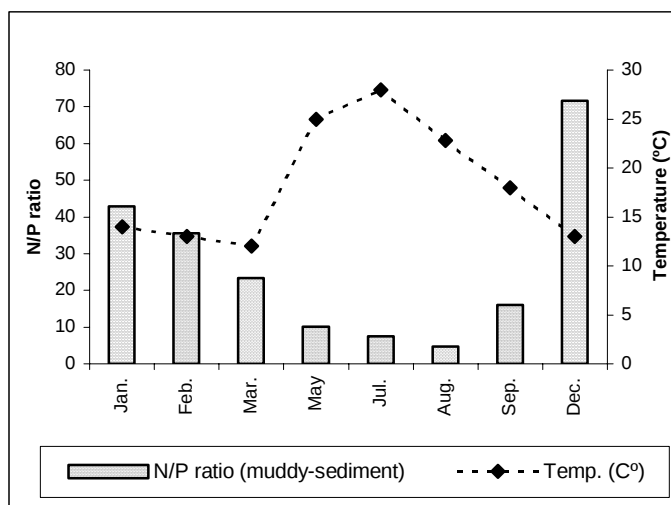


Figure 3-2 - Annual variation of the stoichiometry of ammonium and phosphate fluxes (N/P) with the mean monthly temperature of surface sediments.

Source: Falcão & Vale (1998)

3.4 Major biological aspects

In the Ria Formosa the seasonal variation of primary productivity recorded during neap and spring tides is characterised by lower values in winter, a gradual increase in early spring, and high values in spring/summer (Fig. 3-3).

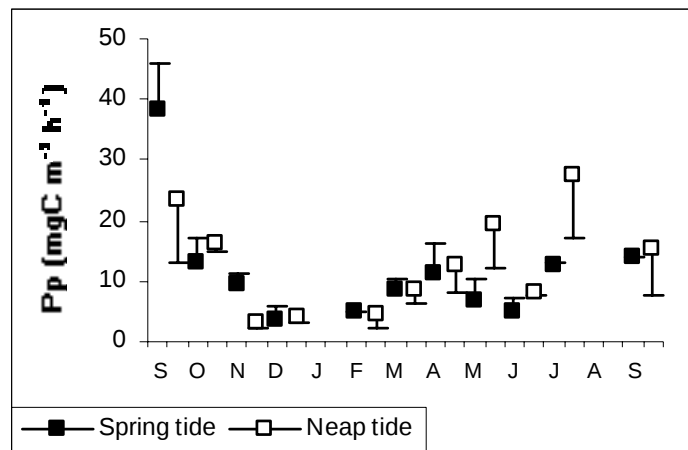


Figure 3-3 - Annual variation of primary productivity (Pp) at neap and spring tides in Ria Formosa. Source: Falcão & Vale (2003)

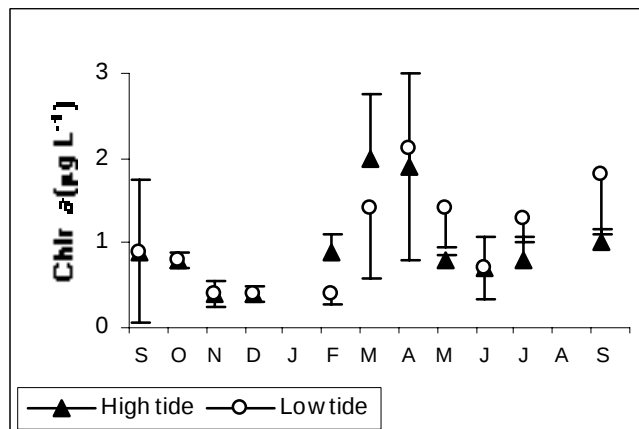


Figure 3-4 - Annual variation of chlorophyll *a* (Chl *a*) concentration, at high and low tide of a neap tide in Ria Formosa. Source: Falcão & Vale (2003)

The period of higher primary productivity does not coincide with that of chlorophyll *a*, the higher carbon fixation occurs later (Fig. 3-3 and 3-4). The carbon fixation rate was highest during summer, when nitrogen compounds were less abundant in the water (Falcão & Vale, 2003).

The lower values of primary productivity in this ecosystem ($2\text{--}9 \text{ mg C m}^{-3} \text{ h}^{-1}$ in winter/autumn) are similar to those obtained in coastal waters, while the higher values ($20\text{--}30 \text{ mg C m}^{-3} \text{ h}^{-1}$ in spring/summer) are comparable to those of the most productive estuarine flats (Falcão, 1997). The photosynthetic efficiency, defined as the ratio between primary productivity and chlorophyll *a*, reach its minimum during the winter period and follow a progressive increase from spring to summer meaning that the maximum yield for carbon fixation rate occurs during summer.

Several studies carried out in this ecosystem to evaluate the primary productivity of inter-tidal microphytobenthos and macrophytobenthos (Falcão *et al.*, 2000 and Proj. OAERRE), have shown a wide annual variability of values. The range of annual values of productivity concerning phytoplankton, microphytobenthos and macrophytobenthos are presented in table 3-5. The biomass estimates of the most important commercial species of consumers (benthic organisms and fish produced in fish farms) are presented in table 3-6.

Table 3-5 - Range of annual values of productivity for phytoplankton, microphytobenthos and macrophytobenthos in Ria Formosa.

Primary Productivity				
Phytoplankton	Microphytobenthos	Macrophytobenthos		
		<i>Zostera</i> sp.	<i>Enteromorpha</i> spp.	<i>Ulva</i> spp.
$\text{mg C m}^{-3} \text{ h}^{-1}$	$\text{mg C m}^{-2} \text{ h}^{-1}$	$\text{mg C g}^{-1} \text{ dw h}^{-1}$	$\text{mg C g}^{-1} \text{ dw h}^{-1}$	$\text{mg C g}^{-1} \text{ dw h}^{-1}$
2.0 – 30.0	10.0 – 50.0	1.0 – 3.0	0.76 – 3.13	2.14 – 6.09

Table 3-6 - Biomass of commercial species of consumers (benthic organisms and fish produced in fish farms).

Benthic organisms	Biomass ton year ⁻¹
<i>Ruditapes decussatus</i> (clam)	5000
<i>Crassostrea angulata</i> (oyster)	2000
<i>Cerastoderma edule</i> (cockles)	1500
Fish	2700

Source: Bulletin from DRPA

3.5 Lagoon Pollution

The concentrations of trace metals in sediments, suspended particles and filter feeders are spatial variable and relatively low in this ecosystem (Cortês *et al.*, 1986). According to these authors the highest concentrations of Zn, Pb, Cu and Cr (434, 60, 110 and 66 $\mu\text{g.g}^{-1}$, respectively) were measured in sediments and particles near the main population centres, while in the channels free from anthropogenic inputs, levels of Zn, Pb, Cu and Cr reached the maximum of 68, 17, 28, and 46 $\mu\text{g g}^{-1}$ respectively, showing no environmental constraints (Report of Project “Estudos de Monitorização do Impacte das Dragagens na Ria Formosa” 1999-2000).

The maximum values of PCB and DDT in mussels (166 and 40 ng.g^{-1} , respectively) and in clams (30 and 4 ng.g^{-1} , respectively) are below the international recommended levels (Castro & Ferreira, 1985). Lagoon sediments show a weak contamination of PCB's. The values obtained for sediments with a large range of organic matter content (from 1 to 12%) were always below 2 ng g^{-1} dw (Castro & Vale, 1995). Other studies carried out in several channels free from anthropogenic inputs presented levels of PCB below 1 ng g^{-1} dw (Project “Estudos de Monitorização do Impacte das Dragagens na Ria Formosa” 1999-2000).

The faecal coliforms (*Escherichia coli* and *Streptococcus faecalis*) present a large spatial variability in the bivalves and in lagoon water. In areas under direct impact of treated and

untreated wastewater discharge, faecal coliforms may reach values between 6 000 and 60 000 FCN/100g fw (areas classified as class C according to legislation- Diário da República n.º 156/2003, II Série, de 9 de Julho). In most part of inter-tidal areas of clam culture the values of faecal coliforms may vary from 300 to 6 000 FCN/100g fw (areas classified as class B according to legislation- Diário da República n.º 156/2003, II Série, de 9 de Julho). In areas without any constraints, levels obtained are below 300 FCN/100g fw (areas classified as class A according to legislation- Diário da República n.º 156/2003, II Série, de 9 de Julho). The faecal coliforms in the lagoon water decrease sharply with the distance from wastewater discharge points due to dilution. In a monitoring program carried out in 2002 near the discharge point of wastewater plants from the main urban centres (Faro, Olhão and Tavira), mean values recorded were between 250 and 1000 MPN/100ml at the distance of 100 m from the discharge point, while values obtained for a distance of 1 000 m were lower than 200 MPN/100ml.

The inner parts of the lagoon under the direct influence of wastewater discharges present higher nutrient concentration levels and consequently the water quality is degraded. In these areas, the ammonium, nitrite and phosphate concentration may reach 30, 2 and 3 μM , respectively while dissolved oxygen reaches sub-saturation levels. These conditions indicate high microbiological activity associated with degradation of organic matter (Newton, 1995). High levels of nutrients were also observed in restricted areas under the impact of river-streams and agricultural runoff. In these areas, during a low tide and a rainfall period, ammonium, phosphates and silicate values of 10, 1.5 and 500 μM , respectively were measured (Newton, 1995). In the extreme parts of the lagoon, with low current velocities, the nutrient levels are controlled by the benthic remineralization. In these areas, oxygen over-saturation is observed indicating that biological activity superimposes the physical and chemical processes (Newton, 1995).

4 MAIN ECONOMIC AND SOCIO-ECONOMIC ASPECTS

4.1 Population

The main urban centres of Ria Formosa are Faro, Olhão and Tavira. Since 1981, resident population has been growing up (Table 4-1). The city with the highest number of resident inhabitants is Faro, whereas the municipality of Tavira has the minor resident population.

Table 4-1 - 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>

In summer occurs a significant population increase due to tourism (non-resident population). During this season, population is almost three times higher than in winter (Mudge & Bebbiano, 1997). It is remarkable that the population centres located along the barrier island system (Ancão, Barreta, Culatra, Armona, Tavira and Cacela islands) also have an extremely variable annual population depending on the main economic activities: tourism, fishing, commerce, and shellfish.

4.2 Aquaculture

Shellfish culture

Shellfish culture has an important contribution to the Algarve's economy. Species of high economical value, like the clam (*Ruditapes decussatus*), and the oyster (*Crassostrea angulata*) are cultivated in the lagoon inter-tidal areas. In these areas, approximately 1587 concessions for

growth banks of clams are in activity (Cachola, 1996). The annual production of clams reaches 5 000 tons year⁻¹, which represents 90% of the regional production while the oyster production reach 2 000 tons year⁻¹ (POOC, 1997).

In the last years, the production of clam decreased probably due to environmental factors that contribute to high mortalities of these benthic organisms. During summer, at neap tide, the chemical and biological processes at the sediment-water interface are very intensive inducing sharp variations of oxygen that may affect filter feeders. According to some studies carried out in the Ria Formosa (Falcão *et al.*, 2000), the mortality of benthic organisms is directly related with the biomass cultivated, anthropogenic inputs from urban areas and the system hydrodynamics.

In this region the shellfish production has a considerable social importance because approximately 10 000 individuals are directly or indirectly involved in this activity (POOC, 1997).

Fish farming

The annual production of fish is about 2700 tons year⁻¹. However, some authors (ICN, 1999) consider that the lagoon potential for fish farming is not fully exploited.

Fish farming is traditionally practised in deactivated salt pans and soils without agricultural aptitude. The offshore fish production is practised in cages, but this method is still in experimental phase (Programa Operacional Pescas/Mare- Estação Piloto off-shore)

The species being produced industrially are the gilthead seabream (*Sparus aurata*) and the seabass (*Dicentrarchus labrax*), which are native species. However, there are research projects in course, to evaluate the potential production of other species like the sole (*Solea senegalensis*) and sargo brems (*Diplodus sargus* and *Diplodus puntazzo*) (Programa operacional Pescas/Mare- Estações Piloto: desenvolvimento e tecnologias de produção).

The fishponds may be made of earth (Figure 4-1) or synthetic materials (like fibreglass), concrete and plastic.



Figure 4-1 - Fishponds in the Ria Formosa lagoon (IPIMAR experimental station -Marim).

The location is a determinant factor for fish farming. Fish production demands good water quality thus the areas near urban and industrial centres are normally excluded due to the risk of pollution. The areas of low elevation above sea level are also excluded because water pumping is difficult. According to the production regime (semi-intensive, intensive and maternity), the exclusion of barrier islands, beaches and tourist sites is also recommended.

This activity demands great investment. Accessibility, availability of energy and local elevation must be considered in order to optimise the cost/benefit relation.

For the offshore fish production it must be established a minimum depth (three times the depth of the cage), a maximum depth (to allow the cage's fixation to the bottom), and a minimum distance between cages. Currents and wave regime are also determinant factors for the implementation of these structures. As for the inshore production, the species cultivated offshore have to be native species. This aquaculture activity may be excluded from the fish banks, navigation routes, areas for nautical sports, with potential risk of pollution and strong currents (near inlets) (Programa operacional pescas/mare- Estação Piloto off-shore).

4.3 Fishing

This lagoon is mostly a nursery place for juveniles of oceanic fish species. More than 1/3 of Algarve's fishery is unloaded in Ria Formosa ports (POOC, 1997). However, fishing is mainly performed in oceanic waters.

4.4 Shellfish catch

Shellfish catch consists in catching bivalves directly from the Ria Formosa natural banks. In the last years shellfish catch overcome the production of shellfish culture (ICN, 1999).

4.5 Salt extraction

The salt extracted in the Algarve represents 50% of the national salt production. A significant part of Algarve's salt is produced in the Ria Formosa salt pans. However, this activity has been declining due to the international competition and the use of ineffective production methods (ICN, 1999).

5 NATURALISTIC ASPECTS, NATURAL, ARTISTIC AND HISTORICAL VALUES

5.1 Natural parks

The Ria Formosa Natural Park was created in 1987 (Legislation - Decreto-Lei n.º 373/87, de 9 de Dezembro). Besides being a Ramsar site and part of the Natura 2000 network, this lagoon system is also a Special Protection Site for Birds (Legislation – Directive 79/409/CEE) and it is included in the National Sites List (Legislation - Habitats Directive-Directive 79/409/CEE).

The park includes a great diversity of habitats, like salt marshes (3430 ha), dunes (1940 ha), saltpans (1130 ha), fish farms (460 ha), sand and mud banks (2000 ha) (<http://www.icn.pt>), freshwater flows, waterside vegetation, agricultural, forest and pine areas, that contribute to a great diversity of flora and fauna.

5.2 Biodiversity

5.2.1 Habitats and associated flora - Sand dunes

The dynamic nature of sand dunes makes them difficult for the fixation and growth of vegetation. The proximity from the sea also creates extreme conditions for plants. Plants are submitted to strong winds, high irradiances, high amplitudes of temperature and bury. Thus, it is not surprising that the sea-faced side of the dunes is so poor in terms of flora. The pre-dune (or primary dune) has an association between some rare species, like the sea rocket (*Cakile maritima*) and the prickly saltwort (*Salsola kali*), at the upper limit of tides. Moving further from the sea and the salt sea breeze, the vegetation gets thicker appearing edifier species like *Elymus farctus* and the marram grass (*Ammophila arenaria*). We may also refer in these areas the sea-spurge (*Euphorbia paralias*) and the sea cottonweed (*Otanthus maritimus*). These plants hold back the movement of sand by the wind and favour the formation of dunes. At the top of the dune appear the species, beach morning glory (*Calystegia soldanella*), sea-holly (*Eryngium maritimum*), maritime crosswort (*Crucianella maritima*), and the marram grass. Further inland, in the inner part of the primary dune, inter-dune and secondary dune several species may be found like the endemic portuguese thyme (*Thymus carnosus*), existing in the Alentejo and Algarve Regions. In the inter-dune space, the specie, *Hypecoum procumbens* (Algarve endemism) is the most relevant. At the sub-hood limit appears the specie, *Pycnocomon rutifolium* that is restricted to the Algarve and to a few Euro-Mediterranean sites.

5.2.2 Habitats and associated flora - Salt marshes

Salt marshes are considered one of the highest productive areas of the biosphere constituting nursery places for many marine species. Here, the slow deposition of sediments promotes the formation of soft soil marked by salinity, humidity and the lack of oxygen. Plants are immersed during high tide and emerged on low tide. Salt marsh vegetation has also a high purification capacity due to the ability of retaining some pollutants compounds.

The bottoms of salt marshes are initially colonized by the small cord-grass (*Spartina maritima*), which supports long immersion periods and exists at low level-areas. After fixed, vegetation slows down the current and accelerates sedimentation rates. The continuous deposition of sediments raises the bottom level and consequently reduces the immersion time and salt concentration. As a result there is a well-defined zonation pattern for salt marsh vegetation. At the low salt marshes (higher-level areas) *Spartina* appear along with *Arthrocnemum perenne* or, in association with *Salicornia nitens*, *Suaeda maritima*, *Atriplex* and *Limonium algarvense* (Algarve endemism). At the upper limit of high salt marshes appears the *Juncus* spp. and *Artemisia campestris* that parasite *Atriplex* and *Suaeda*. The rare specie, *Cistanche phelypaea* may also be found in this area.

5.2.3. Habitats and associated flora – Hoods

The Ria Formosa hoods present great floristic richness, including some endemic species and other species with a special conservation status. Areas of *Pinus pinaster* (wild pine tree) and *Pinus pinea* (pine tree) have replaced the original Mediterranean hood, but there are still specimens representing the old typical flora, like the cork tree (*Quercus suber*) and the olea (*Olea europea sylvestris*). The hoods have a great diversity of bushes, like the *Cistus libanotis* that only occurs on the southwest coasts of the Iberian Peninsula, and the *Tuberaria major*, an Algarve endemism (endangered specie). Medicinal and aromatic plants are also part of Ria Formosa hoods. An example is the rosemary (*Lavandula pedunculata* subsp. *Lusitanica*) and several species of the *Thymus* genera, like the *Thymus lotocephalus*, an Algarve endemism. Endemic

communities of *Tuberario majoris* - *Stauracanthetum boivinni*, *Cistetum libanotis* and *Thymo lotocephali* - *Coridothymetum capitati* exist in the Ria Formosa Natural Park.

5.2.4 Waterside vegetation

Waterside vegetation is very important as food and shelter for aquatic birds. Riverbed and waterside vegetation include species like *Tamarix africana* (tamarisk), *Phragmites communis* (slender reed), *Typha* sp., *Juncus acutus*, amongst others.

5.2.5 Fauna

Associated to plant diversity there is a remarkable abundance of fauna in Ria Formosa. Birds are the main attraction of the lagoon. The strategic position of this lagoon system (between Europe and Africa) makes it an ideal sanctuary for numerous species of migratory birds. Originally from the north of Europe, they find here a shelter for the winter or a resting-place in their journey to the south. From wintering species we may mention the eurasian wigeon (*Anas Penelope*), northern shoveller (*Anas clypeata*), eurasian teal (*Anas crecca*), common pochard (*Aythya ferina*), and the great cormorants (*Phalacrocorax carbo*). There are also numerous limnophilous species like, the kentish plover (*Charadrius alexandrinus*), grey plover (*Pluvialis squatarola*), bar-tailed godwit (*Limosa lapponica*), avocet (*Recurvirostra avosetta*), black-winged stilt (*Himantopus himantopus*), small dunlin (*Calidris minuta*), and the red knot (*Calidris canutus*). The purple swamphen (*Porphyrio porphyrio*) is one of the rarest species of Europe nesting in the Ria Formosa. Important colonies of the little egret (*Egretta garzetta*), white stork (*Ciconia ciconia*), flamingos (*Phoenicopterus ruber*) and grey herons (*Ardea cinerea*) are also found in this Natural Park. The sand dunes and saltpans of the Ria Formosa are a shelter for the little tern (*Sterna albifrons*), a specie in decline over Europe.

The lagoon is also an important nursery and feeding place for numerous species of shellfish and fishes. The most important shellfish species are the clam (*Ruditapes decussatus*), oyster (*Crassostrea angulata*), cockles (*Cerastoderma edule*) and the sword razor shell (*Ensis siliqua*)

due to their economical value. Numerous fish species were identified in the Ria Formosa lagoon (107 species). Few of them are sedentary the others are occasional and migratory. The species of highest economical interest are the gilthead seabream (*Sparus aurata*), common seabream (*Diplodus sargus*), seabass (*Dicentrarchus labrax*), sole (*Solea senegalensis*) and the eel (*Anguilla anguilla*).

The reptile, chameleon (*Chamaeleo chamaeleon*) is a specie threaten to extinction and its distribution in Portugal is restricted to the eastern part of the Algarve.

Mammals like the otter (*Lutra lutra*), genet (*Genetta genetta*), weasel (*Martes foina*), badger (*Meles meles*) and the fox (*Vulpes vulpes*), are also part of the Ria Formosa fauna diversity.

5.3 Heritages

Ria Formosa natural richness makes it a heritage that needs to be preserved. In the lagoon system there are traces of human presence dated from the Neolithic period and some isolated findings from the Palaeolithic. These findings are part of a cultural heritage of undeniable interest. There are signs of Phoenicians, Carthaginians, Greeks, Romans and Arabs. Romans left a decisive legacy, driving the region like never before, specialising in products linked to the sea. Fish farming, fish salting, pottery, naval construction and salt-works are some of the activities introduced by the Romans in the Algarve. Numerous archaeological findings (roman necropolis, baths, mosaic floors and fish salting tanks) confirm the roman presence in the region (<http://www.icn.pt>).

The Islamic presence is revealed on the toponymy, villages, house typology, legends, and vocabulary, but especially on archaeological traces. Recent excavations in “Poço Antigo” (Cacela) exposed a habitational structure, tile fragments and pottery pieces dated from the Islamic period. In Cacela-Velha there are also fragments of ramparts from that period. The Islamic culture is also present in the agricultural methods and utensils, irrigation methods (“nora”) and crops: vegetable gardens, citrinous cultivation, are some of the examples (<http://www.icn.pt>).

6 MODELLING

Previous modelling studies in Ria Formosa included hydrodynamic modelling, to simulate the dispersion of contamination from point-sources (Neves & Martins, 2002), and biogeochemical modelling to simulate nutrient dynamics, phytoplankton productivity, oxygen concentrations and bivalve growth (Falcão *et al.*, 2000).

The former authors used a lagrangean version of the two-dimensional vertically integrated hydrodynamic model described in Neves (1985), to estimate the water residence times in different bivalve rearing areas of Ria Formosa and to simulate bacterial dispersion from the main pollution point-sources. Water residence times are shorter in those areas classified as most suitable for bivalve production.

The zero-dimensional biogeochemical model of Falcão *et al.* (2000) was used to estimate Ria Formosa carrying capacity for clam (*Ruditapes decussatus*) culture. The model was implemented in EcoWin (Ferreira, 1995). EcoWin uses Object Oriented Programming (OOP) to relate a set of "ecological" objects by means of a server or shell that allows these to interact with each other, and displays the results of their interaction. Both the EcoWin shell and the objects have been programmed in C++ for WindowsTM. Separate objects were implemented to simulate:

- 1) Light intensity;
- 2) Water temperature;
- 3) Dissolved oxygen, nutrients and suspended matter concentrations;
- 4) Phytoplankton production and biomass;
- 5) Microphytobenthos and macrophytobenthos production;
- 6) *R. decussates* metabolism, growth and population dynamics.

Light intensity and water temperature were simulated by standard formulations described in Brock (1981) and Portela & Neves (1994). Other processes were simulated with equations and parameters described in Falcão *et al.* (2000) and following an approach similar to that described in Ferreira *et al.* (1998). Photosynthetic rates were calculated with the Steele's equation (Steele, 1965), for phytoplankton and microphytobenthos, and with a Michaelis-Menten equation, for

macrophytobenthos (mostly *Zostera marina*). *R. decussatus* physiology was based on experimental data reported in Sobral (1995). Clam mortality rates in different cultivation areas were estimated from experimental results described in Falcão *et al.* (2000). The mathematical description of population dynamics is similar to that given in Ferreira *et al.* (1998) for the oyster *Crassostrea gigas*.

The model was applied to different cultivation areas. Dilution of local water properties was calculated by advection-diffusion estimated from tidal amplitudes and known water residence times. One of the main objectives was to evaluate the impact of different clam culture densities on oxygen concentrations in trying to explain summer mortality outbreaks, coincident with high water temperatures and low water renewal rates during neap tides. Dissolved oxygen concentrations depended on advection-diffusion, air-water exchanges, photosynthetic production and respiration by all biologic components: phytoplankton, microphytobenthos, macrophytobenthos and clams. A brief synthesis of the results obtained is given in the next paragraphs.

In Figure 6-1 predicted and observed water temperatures are shown. As it can be seen, the model reproduces accurately water temperature dynamics. In Figure 6-2 predicted and observed dissolved oxygen concentrations over one year are shown. Again, there is a reasonable agreement between model and observations. In Figure 6-3, predicted dissolved oxygen concentrations under various *R. decussatus* biomass densities are shown. According to model predictions, high densities ($> 3 \text{ kg FW m}^{-2}$) may produce night time oxygen minimums below 28 % saturation, which corresponds to the critical threshold below which scope for growth becomes negative in this species (Sobral, 1995). Figure 6-4 compares observed and predicted phytoplankton concentrations over a year. Two sets of predictions are shown: one based on a maximum photosynthetic rate of 0.05 h^{-1} and another based on a value of 0.35 h^{-1} . In Figure 6-5 observed and predicted clam growth for a period of one year is shown. There is a good agreement between predicted and observed data. Finally, in Figure 6-6 the results of the demographic model are presented, depicting the evolution of *R. decussatus* population structure over a period of one year.

From experimental data and model simulations, Falcão *et al.* (2000) concluded that clam densities in Ria Formosa should be kept below densities of 2 kg FW m^{-2} to prevent high summer mortalities.

Recently, Duarte & Pereira (in prep) developed a new modelling tool called EcoDyn with the purpose to couple the hydrodynamic model of Neves (1985) with the above mentioned biogeochemical objects. This new tool follows an approach similar to that of EcoWin, except that it was specifically designed for coupled physical-biogeochemical modelling. All objects representing the different physical and biogeochemical processes are implemented in C++ and compiled as Dynamic Link Libraries (DLLs). This will allow their utilisation from other programming tools in windows environment. The hydrodynamic object for Ria Formosa was already tested with EcoDyn. It is based on a finite difference bathymetric staggered grid (Vreugdenhil, 1989) with a spatial resolution of 200 m. In Figure 6-7 some results are shown on the velocity fields predicted by the model during low and high tide. The coupling of the hydrodynamic and the biogeochemical objects is in underway.

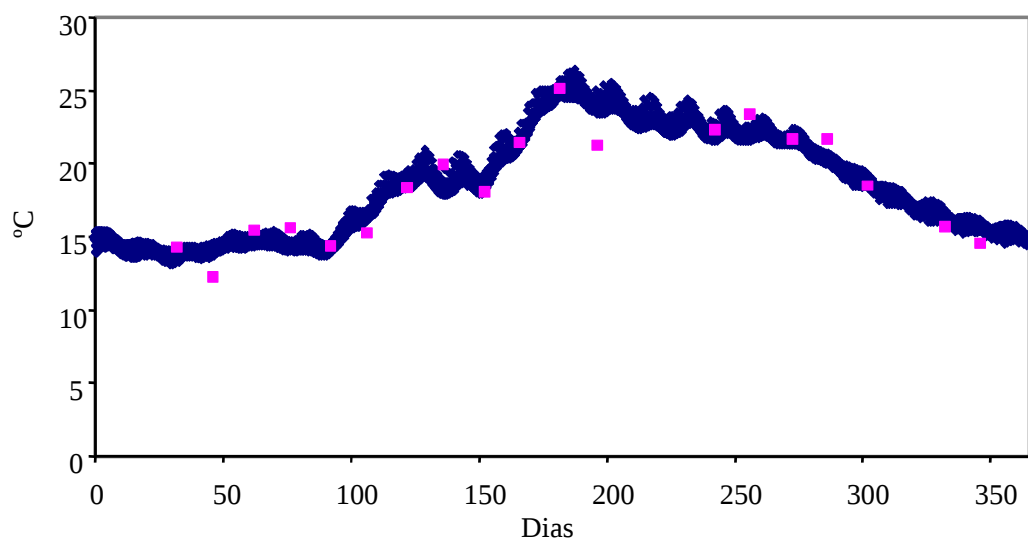


Figure 6-1- Predicted (squares) and observed (line) temperatures over a year (see text).

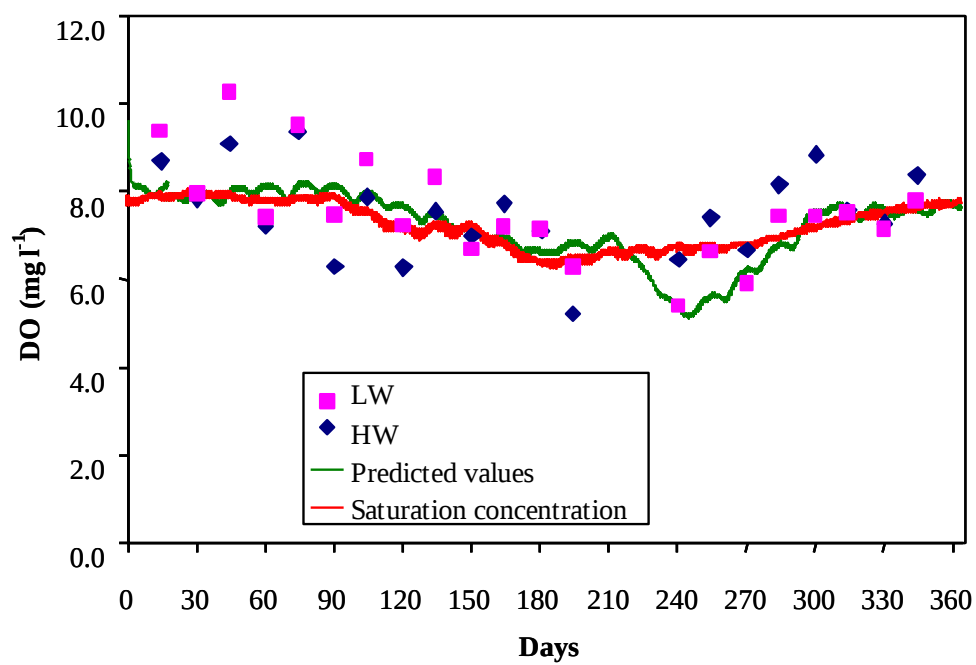


Figure 6-2- Observed (symbols) dissolved oxygen (DO) during low water (LW) and high water (HW), predicted (green line) and saturation values (red line) over one year.

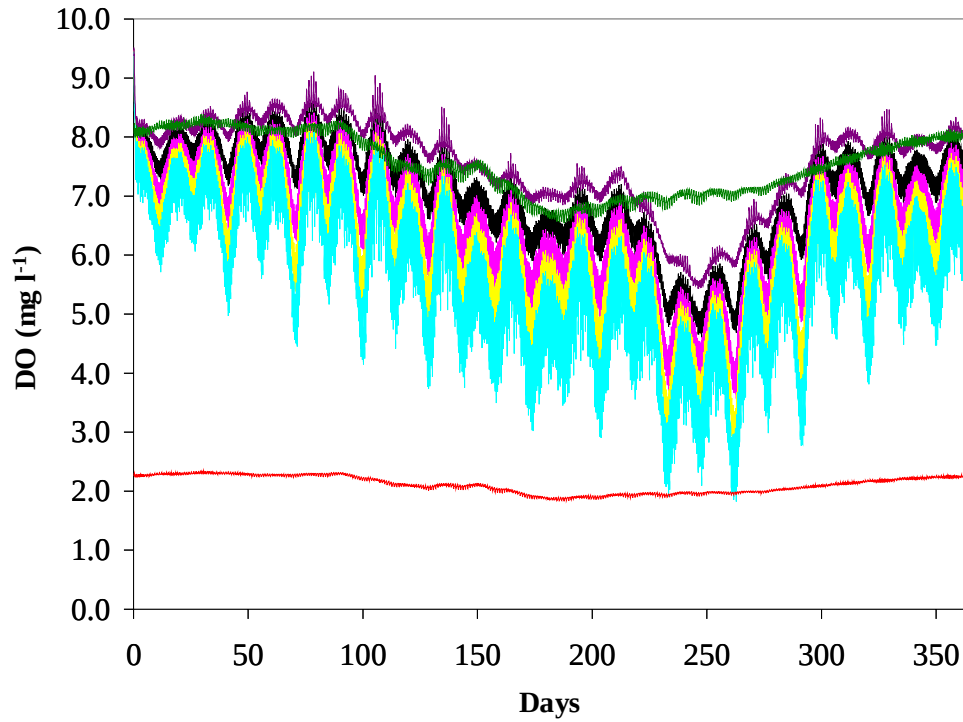


Figure 6-3- Dissolved oxygen saturation concentration —, predicted values under different biomass standing stocks of *R. decussates*; — 0 kg m⁻², — 1 kg m⁻², — 2 kg m⁻², — 3 kg m⁻², — 4 kg m⁻² and — line depicting 28 % dissolved oxygen saturation (see text).

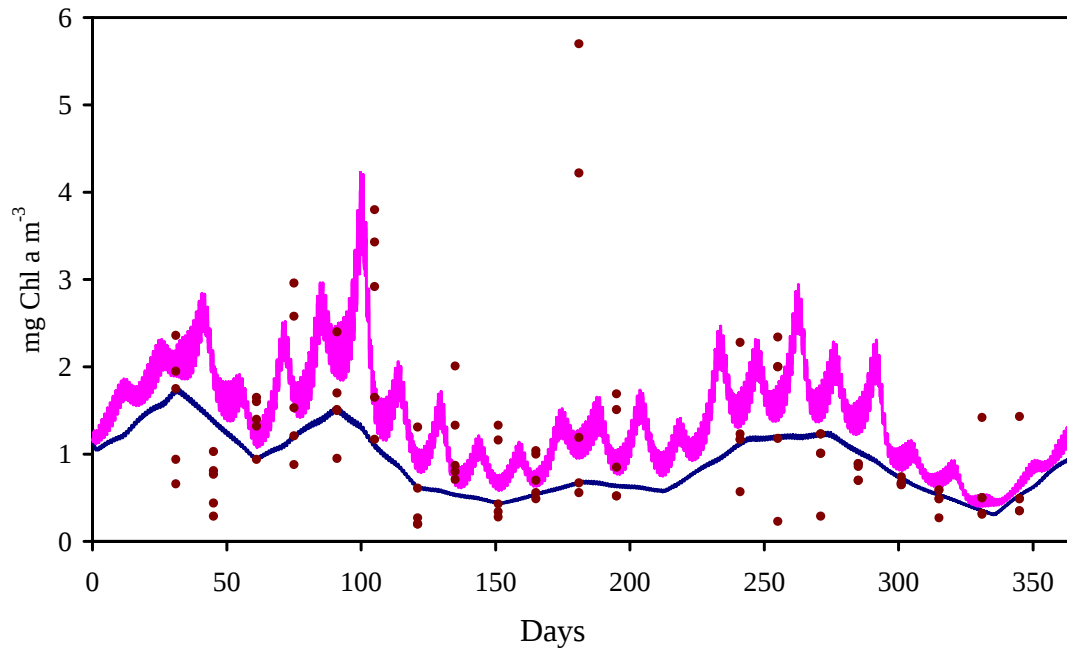


Figure 6-4 - Predicted (points) and observed (lines) phytoplankton concentrations over a period of one year with a P_{max} of 0.05 h⁻¹ — and with a P_{max} of 0.35 h⁻¹ — (see text).

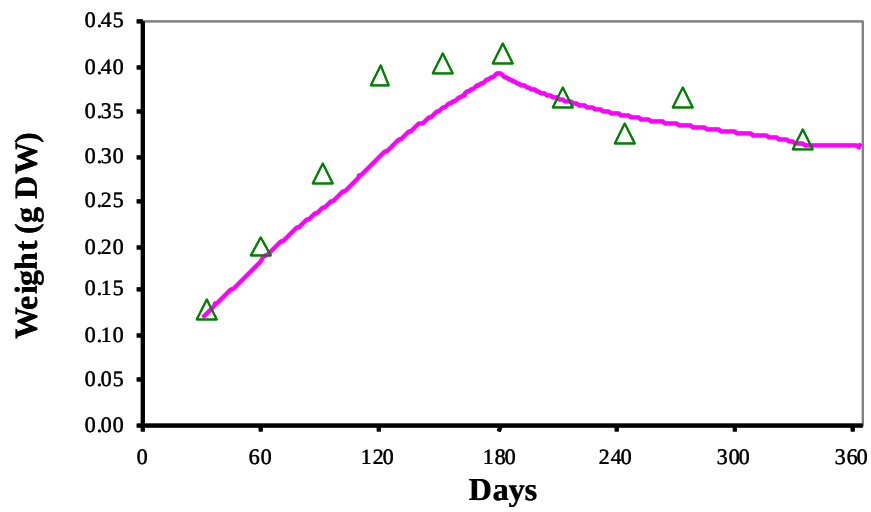


Figure 6-5 - Observed (symbols) and predicted *R. decussatus* growth over a year (see text).

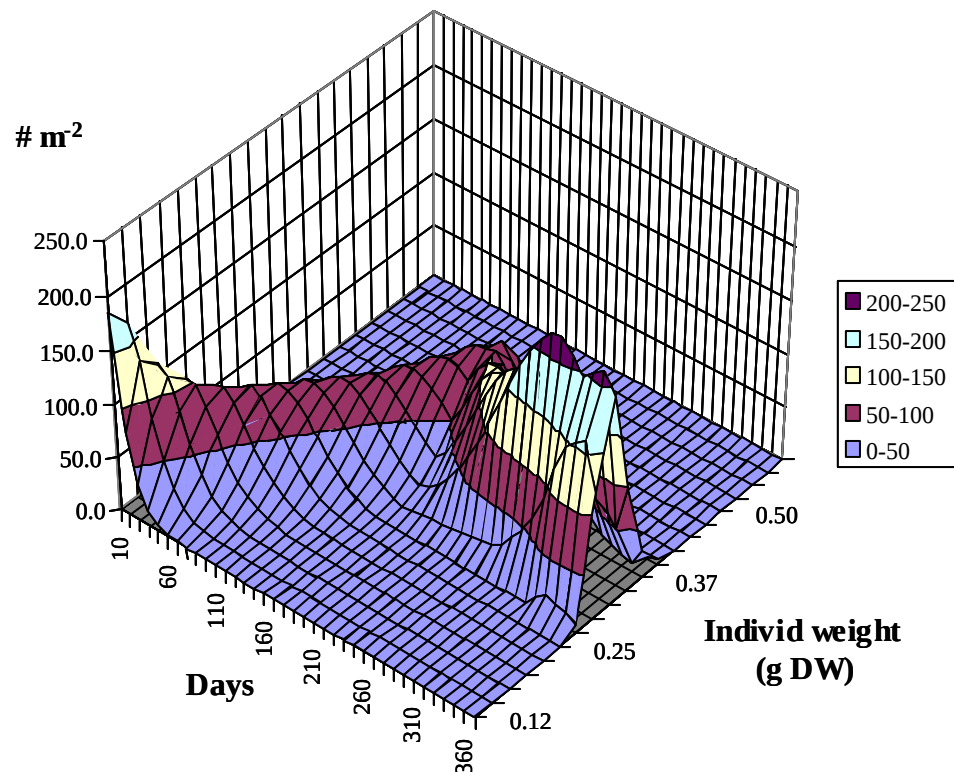


Figure 6-6 - Predicted *R. decussatus* population dynamics over a year (see text).

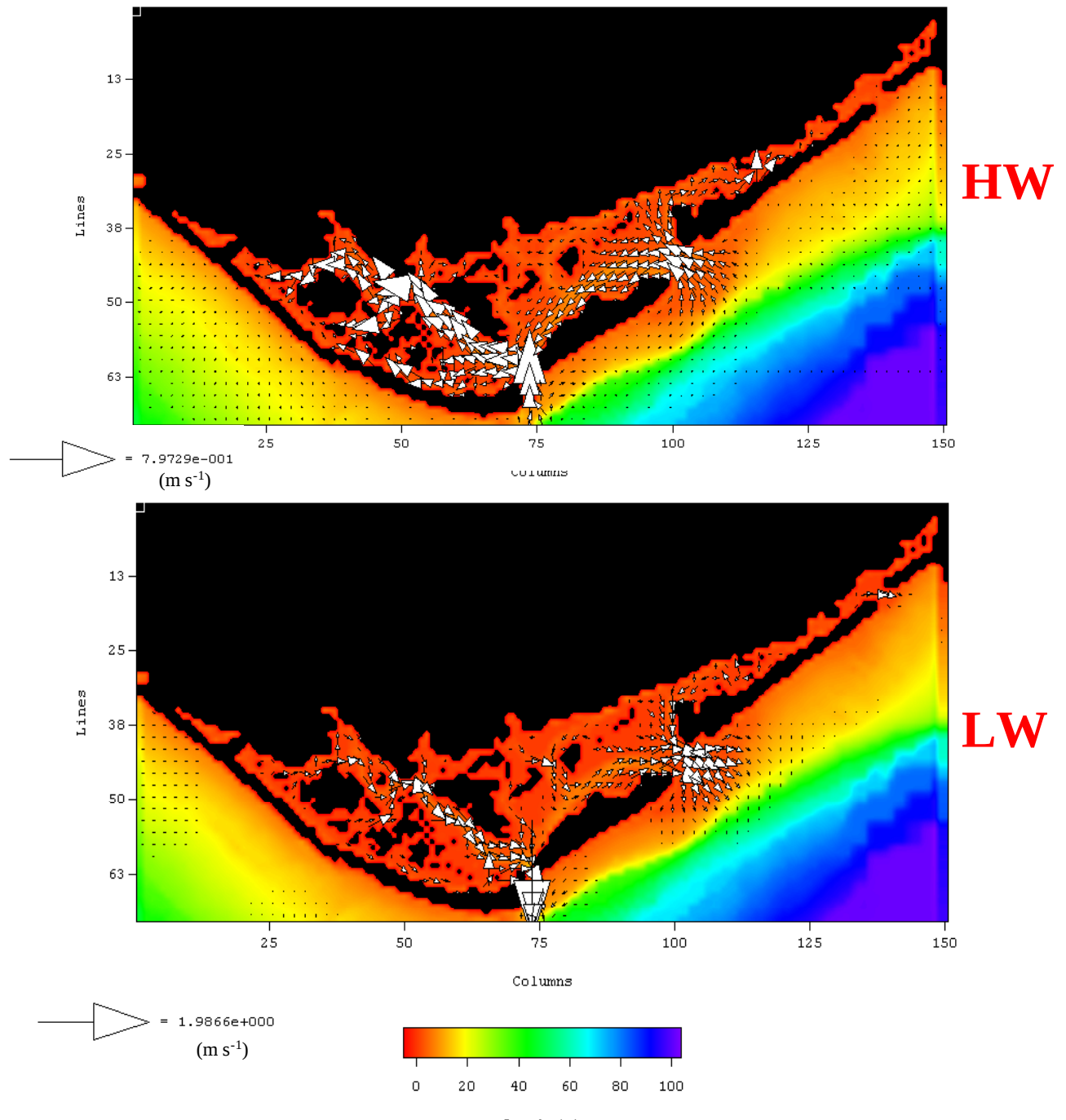


Figure 6-7 - EcoDyn hydrodynamic object. Velocity fields predicted by the model in a low water (LW) and a high water (HW) situation.

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