Biogeochemical Modelling of Ria Formosa (South Portugal)

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Abstract

Ria Formosa is a large (c.a. 100 km^2) mesotidal lagunary system with intertidal areas with conflicting uses such as fisheries, aquaculture, tourism and nature conservation. Its watersheds cover an area of approximately 864 km^2, with a perimeter of 166 km and a maximum altitude of 522 m. Land use may be classified into six major groups: 1) urban, 2) agricultural, 3) forest, 4) rangeland and pastures, 5) wetlands and 6) water bodies. The main objectives of this work are to: (i) Evaluate the relative importance of land drainage, waste water treatment plants (WTP) and water exchanges across the lagoon inlets, for nutrient dynamics; (ii) Analyse management scenarios related to changes in lagoon bathymetry and their potential effects on system dynamics. The Soil and Water Assessment Tool (SWAT model) has been applied to the catchment areas in order to simulate water discharges into Ria Formosa providing forcing to a two-dimensional vertically integrated coupled physical-biogeochemical model, implemented with EcoDynamo – an object oriented modelling software. This model includes water column and sediment processes as well as their interactions and several biological sub-models (e.g. phytoplankton dynamics and bivalve growth). Obtained results suggest that the river network may have a significant effect on lagoon concentrations, in spite of the relatively low river flows, due to the high ammonium and nitrate loads. Scenarios reflecting increases in lagoon bathymetry through dredging operations suggest an increase in lagoon water washout time with potential impacts on water quality and impacts at a scale of tens of km. The obtained results are being used by the Ria Formosa Natural Park authority for management purposes and may be useful to feedback future updates of the watershed management plans, within the scope of the European Union Water Framework Directive. The use of a lagoon scale models is therefore justified in this work.

1. Introduction

The European Water Framework Directive (WFD) (EU, 2000) introduced important changes on the way water is managed in European Union countries. One of the most important aspects of this directive is the recognition of the close link between watersheds and coastal waters, namely by defining "River basin district" – made up of river networks, groundwater and associated coastal waters - as the main river basin management unit (EU, 2000). This fact is in line with an increasing tendency to link watershed, hydrodynamic and water quality models (e.g. Park et al., 2003; Plus et al., in 2006). The development and implementations of such integrated approaches is one of the main goals of the European Union DITTY project (Development of an information technology tool for the management of Southern European lagoons under the influence of river-basin runoff), where watershed and coastal lagoon models are being applied to five different southern European ecosystems: Ria Formosa (Portugal), Mar Menor (Spain), Thau lagoon (France), Sacca Di Goro (Italy) and Gulf of Gera (Greece). Several technical reports are available at the project web site (http://www.dittyproject.org/). The general approach is to use an offline coupling of watershed and lagoon models, with the former producing forcing conditions for the latter in terms of river flows, nutrient and suspended matter loads (Plus et al., in 2006).

One of the consequences of the WFD is the need for involved countries to produce studies synthesising the state of their waters and applying the classification scheme defined in the Directive. Within this classification scheme, coastal lagoons classify as "Surface water" and typically as "Transitional water" or "Coastal water", depending on whether they are substantially influenced by freshwater flows or not.

At present, there is no general agreement about which models to use to simulate watersheds and coastal lagoons. Searching the literature reveals that there are tens of different models, that have been applied by

several authors, e.g. Chapelle et al. (2005a). Over the last years, there has been an increasing tendency to couple hydrodynamic and biogeochemical models in a clear recognition of the importance of incorporating the feedbacks between physical, chemical and biological processes.

Ria Formosa is a natural park and one of the largest Portuguese coastal lagoons, where many conflicting uses coexist such as fisheries, aquaculture, harbour activities, tourism and nature conservation. The watershed draining to this coastal lagoon flows mostly though agricultural lands, where there has been some intensive use of fertilizers. Management of this coastal ecosystem involves several institutions such as the Natural Park Authority, several municipalities and the Portuguese Navy. Within the scope of the above mentioned DITTY project, several possible management scenarios were defined by the Natural Park Authority, that are being evaluated from the environmental and economic point of view, by using an hydrologic model for the watershed and a coupled hydrodynamic-ecological model for the lagoon. This work represents the first approach to this scenario analysis and its objectives are:

(i)   Analyse management scenarios related to changes in lagoon bathymetry and their potential effects on system dynamics.

(ii)   Evaluate the relative importance of land drainage, WTP plants and water exchanges, across the lagoon inlets, for nutrient and suspended matter dynamics;

This study is not a complete assessment of the consequences of the scenarios referred above or of nutrient and suspended matter discharges, but solely a first attempt to approach their effects at the lagoon scale.

2. Methodology

2.1 Site description

2.1.1 Watershed

Ria Formosa watershed is located at the Southernmost part of Portugal (Fig. 1). The origin of its rivers is mostly in the Caldeirão mountain range and its water courses drain perpendicular to the South in the direction of the Atlantic Ocean. Most of the rivers are ephemeral with no runoff or very reduced runoff during part of the year, between June and December. The Ria Formosa basin has an area of 864.26 km^2, a perimeter of 165.99 km, with a maximum altitude of 522 m, draining to the ocean, and an average altitude of 112m, with an average slope of 17% (MAOT, 2000).

Based on annual and monthly data there seems to be an increase in irregularity in annual precipitation in the basin, being the average annual precipitation value between 600 and 800 mm. 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. As far as maximum daily annual precipitation, for a return period of 2 years, the value is approximately 55 mm, whereas for a 100 years return period it is 132 mm.

2.1.2 Coastal lagoon

Ria Formosa is a shallow mesotidal, eurihaline lagoon located at the south of Portugal (Algarve coast) with a wet area of 105 km^2 (Fig. 1), classified as "Coastal waters" (INAG, 2005) within the scope of the Water Framework Directive (EU, 2000). The lagoon has several channels and a large intertidal area which corresponds roughly to 50% of the total area, mostly covered by sand, muddy sand-flats and salt marshes. The intertidal area is exposed to the atmosphere for several hours, over each semi-diurnal tidal period, due to its gentle slopes. Tidal amplitude varies from 1 to 3.5 meters and the mean water depth is 3.5 m (Falcão et al., 2003).

2.2 Hydrologic modelling of the watershed

In this work the SWAT model was used to calculate river flows to force an ecological model of the lagoon. SWAT, acronym for Soil Water Assessment Tool is a model developed by the USDA Agricultural Research Service to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. It is a continuous time model, not designed to simulate detailed, single-event flood routing (Neitsch et al., 2002).

Rainfall data used in this project is freely available from INAG, which is the Portuguese Water Institute (www.inag.pt). There are five rain gauges within the Ria Formosa basin area with daily, monthly, yearly and maximum 24 hour precipitation records. Daily rainfall records were used to run the SWAT model. This model allows for missing records and uses a weather generator to fill in for these gaps.

Most water that goes into the soil is used by plants through transpiration. Nonetheless, water can percolate through the soil until it reaches the aquifer and recharge it. Water may even move laterally in the profile and contribute to stream flow. Therefore, an accurate representation of soil characteristics is important for a reliable output of the SWAT model. Soils data were obtained from Atlas do Ambiente (IA, 2005) as shape files to be used by ArcGis. Associated soil characteristics were obtained from a 1965 publication (Cardoso, 1965) and were inserted in the SWAT data base. The soil types present in the Ria Formosa basin are Cambisols, Fluvisols, Lithosols, Luvisols, and Solonchaks, being Lithosols predominant in the upper basin and Cambisols and Luvisols in the lower region. As far as the coastal system itself, the predominant soil type is Solonchak (PROCESL et al., 2000).

Ria Formosa basin has a wide variety of land use classes. Land use data at a 1:25 000 scale was obtained from the Corine Land Cover maps. There are about 100 different land use classes being divided among six major groups: 1) urban, 2) agricultural, 3) forest, 4) rangeland and pastures, 5) wetlands and 6) water bodies. For SWAT applications, land use data was aggregated within these six land use types, and some land uses

were further divided for better description in the Ria Formosa basin and the result was a total of eleven land use classes in the basin (Fig. 2).

As indicated by Neitsch (2002), calibration of a SWAT model run can be divided into several steps:

• water balance and stream flow

• sediment

• nutrients

For the purposes of this work, calibration was performed on stream flow only. Sediment and nutrient loads, for forcing the lagoon model, were computed from flows and measured concentrations. One stream flow gauge was used for calibration, Bodega, being the one with most data records. Coiro da Burra has less than one year of monthly flows, including missing data in the data set, and therefore it was neglected in the calibration. Curral Boieiros was used for the validation of SWAT parameters (Fig. 1).

As suggested by Neitsch (2002), "calibration for water balance and stream flow should be first done for average annual conditions, and once the model is calibrated for average annual conditions, the user can shift to monthly or daily records to fine-tune the calibration" and, therefore, calibration was performed in this order.

The model was calibrated for annual volume using the data set from the Bodega streamflow gauge, in order to have some understanding of the actual conditions in the watershed. Calibration was performed manually, by slightly changing land use and soil variables.

The output from SWAT annual runs is in civil years, rather than water years and that was the time span used for the analysis. Annual stream flow data published by INAG (www.inag.pt) is in water years, and therefore, for the annual analysis, monthly data was used for calculation of annual flows, simply adding up all monthly flows within a civil year. Bodega data set has no missing records from 1953 to 1982, on 1984, and from 1986 to 1988. Records from those years were used in the analysis.

In order to calibrate stream flow, the curve number parameter was adjusted until modelled surface flow values were approximately the same as stream flow records. This value was adjusted within reasonable limits for watershed soil, land use and management characteristics. Further adjustment of available soil water capacity was needed and was performed also within reasonable limits. Most streams are ephemeral, including the ones in which the stream flow gauges are inserted, being baseflow calibration difficult to perform.

The overall correspondence between data records and modelled values was analysed using Model II linear regression analysis, as suggested by Laws and Archie (1981), with the major axis regression method as recommended by Mesplé et al. (1996) and described in Sokal and Rohlf (1995). ANOVA was used to test significance of slopes and y-intercepts, as well as the variance explained by the model.

2.3 Hydrodynamic and biogeochemical modelling of the lagunary system

The ecological model implemented in this work is a two dimensional vertically integrated model based on a finite difference staggered grid (100 m resolution in the present case), coupling hydrodynamic, thermodynamic and biogeochemical processes. It calculates the velocity field with the equations of motion and the equation of continuity (Knauss, 1997) and solves the transport equation for all water columns variables:

$$\frac{dS}{dt} + \frac{\partial(uS)}{\partial x} + \frac{\partial(vS)}{\partial y} = A_x \frac{\partial^2 S}{\partial x^2} + A_y \frac{\partial^2 S}{\partial y^2} + Sources - Sinks \qquad (1)$$

Where,

u and *v* - current speeds in *x* (West-East) and *y* (South-North) directions (m s^{-1}); *A* – Coefficient of eddy diffusivity (m^2 s^{-1}); *S* – A conservative (Sources and Sinks are null) or a non conservative variable in the respective concentration units.

Calculated biogeochemical processes provide the values for the *Sources* and *Sinks* terms of equation 1 at each grid cell.

In the present model, water circulation is forced by tidal height variability and river discharges at sea and river boundaries, respectively. Tidal height is calculated from the harmonics of the Faro-Olhão harbour reported in SHOM (1984). The 2D solution for the Navier-Stocks equations is the same described in Neves (1985), using an ADI (alternating direction implicit) scheme (Dyke, 2001). One important feature of this model is to include a wet-drying scheme to avoid numerical errors when intertidal areas run out of water. As described by the previous author, this consists in interrupting flows in those grids cells where water level drops below a critical value (5 cm in the present case). To guarantee that these cells may be refilled again, they are considered in the calculations when one of the neighbour cells has a higher water level, allowing for water to be driven into the "dry" cell by the pressure gradient force.

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 the previous author. 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 Duarte et al. (2005) and 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 Martin et al. (2003) was followed.

The model was implemented with EcoDynamo (Pereira & Duarte, 2005) – an object oriented software written in C++. Table 1 summarizes the objects implemented and their corresponding variables and processes. Each object simulates several variables and processes and corresponds roughly to the usual understanding of a sub-model. However, objects have several specific properties that make them very suitable for modelling, such as modularity, inheritance and polymorphism (Ferreira, 1995).

In EcoDynamo, available objects may be plugged in and out though the model interface, to evaluate the relative importance of different variables and processes on model solutions. There are two main different running modes – one with an online coupling of hydrodynamic and biogeochemical processes and another with an offline coupling. The latter uses previously obtained and time integrated (for 5 minute periods) data series of current velocities with the hydrodynamic object, to transport water properties among model grid cells. This allows for a faster simulation, avoiding the computation overhead of hydrodynamic processes and the small time steps generally required. This simplified mode was used in the present work. Whereas "online coupling" needs a 3 s time step for stability restrictions, mostly because of very low depths over intertidal areas, the offline simulations may use a time step of up to 30 s. In fact, a variable time step is used, so that sites where instabilities may arise are resolved with more detail and properly time integrated with neighbour cells. Instabilities generally occur when the volume in a cell is very low. In this case, if the time step is not small enough, the computed flow across one of the cell "walls" times the time step, may be larger than cell volume. When calculating transport of salt or any other property, this situation may lead to the violation of mass conservation. The algorithm consists in resolving with more detail these "critical cells" and their interactions with neighbour cells, finding a time step small enough to prevent mass conservation violations.

In the current model there are no feedbacks from biogeochemistry towards hydrodynamic processes. This is generally true in barotropic models. In baroclinic simulations, water temperature and density may be influenced by water turbidity that changes, among other things, as a result of phytoplankton concentration variability.

The simulations analysed in the present work were 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 1). The simulations were designed to understand the relative contribution of specific processes within the western part of Ria Formosa (Fig. 1), according to the objectives referred above (cf. – Introduction), and may be viewed as a "virtual" experiment, with a few simplifying assumptions. Their accuracy depends mostly on the quality of the hydrodynamic simulation. Therefore, the calibration and validation of the hydrodynamic object is analysed in this study and based on current velocity data collected by the Portuguese Hydrographic Institute in 2001 (IH, 2001) at a number of stations (Fig. 1), over periods of several days (not necessarily coincident among different stations), between January and March 2001. 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). A study using the full model complexity, including its calibration and validation is currently being carried out and it will be the subject of an upcoming paper.

A first set of hydrodynamic simulations was carried out for the same period used in model calibration/validation to analyse the effects of several scenarios related to changes in lagoon bathymetry and depicted in Fig 3. These scenarios were defined by Ria Formosa Natural Park staff on the basis of past dredging activities and anticipating the need to improve navigation conditions within some of the main channels. Results from the various simulations were analysed by comparing obtained water washout times, time integrated flows across the inlets and current velocities at points used for model calibration/validation. Water residence times were estimated by "filling" the lagoon with a conservative tracer and running the model until its "washout" to the sea.

A second set of simulations (Table 2) was performed to understand the relative importance, on Ria Formosa water quality, of flow discharges from rivers and from Waste Water Treatment Plants (WWTPs), and of

conservative and some non-conservative processes. In this case, the offline mode was adopted (see above). Two river flow regimes were considered – winter and summer - estimated with the SWAT model (see above). Comparing results obtained with different river discharge regimes (nearly zero discharge for the summer situation) or/and WWTP discharges permits to understand the relative contribution of land drainage and WWTPs 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.

3. Results

3.1 Hydrologic modelling

As far as annual flow, SWAT adequately models it, as can be observed from Fig. 4 and from the results of Model II linear regression analysis performed. The slope of the Model II regression between data records and modelled values was not significantly different from one and the y-intercept was significantly different from zero ($p < 0.05$). The variance explained by the model was significant ($p << 0.05$). These results imply that the model explains a significant proportion of the observed variance. However, the model tends to overestimate measured annual flows.

Analogous to annual flow, monthly flow is adequately modelled by SWAT, as can be observed from Figs. 5 and 6 and from Model II linear regression analysis performed. The variance explained by the model was

significant ($p \ll 0.05$) in most months, except the summer months of July, August and September. This is probably due to the absence of rain during those months in which the model cannot predict the stream flow well. Slope between data records and modelled values was not significantly different from one and y-intercept was not significantly different from zero ($p < 0.05$) except on the summer months.

3.2 Hydrodynamic and biogeochemical modelling of the lagunary system

In Figs. 7 – 10, measured and predicted current velocities are shown for each of the monitoring locations depicted in Fig. 1 at the western part of Ria Formosa. The visual fit between measurements and observations is generally good. The slope of the Model II regression between measured and observed values (cf. – Methodology – Hydrologic modelling) was significantly different (s.d.) from one and the y-intercept was s.d. from zero ($p < 0.05$) in almost all simulations. The variance explained by the model was significant ($p \ll 0.05$) in all cases. These results imply that the model explains a significant proportion of the observed variance. However, it tends to underestimate measured velocities. This is an expected result, because model velocity predictions correspond to spatially integrated values for each grid cell, whereas measurements are performed in one point in space, within the channels, where current velocities tend to be higher.

Ideally, two independent data sets should have been used – one for calibration and another for validation. However, since there was only one dataset available and since the model reproduced observed data relatively well, without any calibration effort, calibration and validation are here considered together. Furthermore, changing model parameters locally, such as turbulent diffusivity or bottom drag, seeking for a better model fit to observed data, would hardly be consistent in future simulations, in a system where bottom configuration and bathymetry changes so rapidly. Therefore, efforts were mostly directed towards a rigorous bathymetric description and the determination of the accurate position of all inlets at the time when sampling surveys were carried out.

Current speeds range from nearly zero till values in excess of 100 cm s^{-1}. Velocity peaks occur both at the middle of the ebb and the middle of the flood. This is a normal phenomena in inlets - when current switches from flood to ebb, the water level is near its peak flood value (Militello & Hughes, 2000). General circulation patterns within Ria Formosa are shown in Fig. 11, during the flood and during the ebb. Maximum current velocities are observed at the inlets. During the ebb, water remains only in the main channels. Residual flow suggests the existence of eddies near the inlets and also close to Faro-Harbour (cf. – Fig. 1). The comparison of ebb and flood tidal periods, predicted by the model, confirms flood dominance (Table 3). According to model results, the flood period may be larger than the ebb period by nearly two hours in Ancão, and Fuzeta-Canal. These patterns may be explained by flow divergence (see below).

The integration of flows across the inlets made possible to estimate their average input-output values for a period of a month. In Fig. 12, 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 (cf. Fig. 11), probably reducing the flood period in other areas. The results presented in Table 3 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.

Table 4 summarizes the results of the first simulation set (cf. – Methodology - Hydrodynamic and biogeochemical modelling of the lagunary system), where the effect of several changes in lagoon bathymetry

on the time necessary for the washout of 50, 90 and 99% of lagoon water, time integrated flows across the inlets and current velocities at chosen points were investigated.

Table 5 summarizes the results of the second simulation set (cf. – Methodology - Hydrodynamic and biogeochemical modelling of the lagunary system), to investigate the effects of flow discharges from rivers and from WWTPs, and of conservative and some non-conservative processes on water quality.

4. Discussion

SWAT model was successfully calibrated and validated except for the summer (dry) months, where the streams have a low flow or no flow at all. The average river flow draining to "Western" Ria Formosa is c.a. 0.4 m^3 s^{-1}, a rather low figure considering the size of the lagoon. The model was used for the Ria Formosa basin system to generate annual, monthly and daily average flows as input to the lagoon model presented in this study, after its successful calibration and validation.

Obtained results with the lagoon model (first simulation set, cf. 2.3 and 3.2) show that channel deepening though dredging operations tends to increase water washout time (cf. Table 4), 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. 3) 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.

The results obtained wit the second simulation set (cf. 2.3 and 3.2) 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 (cf. - Fig. 2). However, the model predicts a rapid decline in nitrate concentrations with distance from river mouths (Fig. 13). It is noteworthy that ammonium concentrations practically double when TPM or nutrients are treated as non-conservative (Table 5, simulations 4, 5 and 6), as a result of POM mineralization or denitrification, respectively. This doubling is much larger than the combined effect of river and WWTP discharges. It is also relevant to see that WWTP 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" (cf. – Methodology – Site description). 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 6, 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 macrolgae 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 doubling time (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 6). 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 in Ria Formosa (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).

Obtained results also suggest the importance of other sources of nutrients than the watershed in Ria Formosa biogeochemistry, such as nitrogen fixation, inputs from the sea and sediment water interactions.

5. Conclusions and future work

From the results presented and discussed, it may be concluded that scenarios related to changes in lagoon bathymetry tend to increase lagoon water washout time. This result is explained by an increase in lagoon volume without a corresponding increase in current velocity. The Faro-Olhão and the Fuzeta scenarios are

those with a largest impact, since they result in the largest effect on washout time. Changes in lagoon bathymetry may have impacts at a scale of tens of km away, as seen by changes on average inflows and outflows across inlets located far away from dredged areas (cf. Table 4). This conclusion justifies the usage of a lagoon scale model, as in the present work.

Watershed and WWTP contribution is mostly through nitrate loads, whereas WWTP contribution is mostly through ammonium loads. From a management point of view, dredging operations are important to improve navigability, but may have a negative impact on water quality if water washout time is increased. Furthermore, this increase may have important implications in lagoon biogeochemistry due to the apparent dependence of nutrient cycles on lagoon-sea exchanges.

The results obtained in this work and corresponding conclusions help to understand the relative importance of the watershed at this part of the river basin district (EU, 2000) called "Ribeiras do Algarve", suggesting that the high nitrate concentrations at the river network may have a significant effect on lagoon concentrations, in spite of the relatively low river flows.

Acknowledgements

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Table 1 – EcoDynamo objects implemented for Ria Formosa and respective variables (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 fluxes and 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 (ammonia, nitrate and nitrite), inorganic phosphorus and oxygen, sediment adsorbed inorganic phophorus, organic phosphorus, nitrogen and carbon
	Dissolved substances object	Dissolved inorganic nitrogen (ammonia, nitrate and nitrite), inorganic phosphorus and oxygen
	Suspended matter object	Total particulate matter (TPM), particulate organic matter (POM), carbon (POC), nitrogen (PON),phosphorus (POP) and the water light extinction coefficient
	Phytoplankton object	Phytoplankton biomass, productivity and cell nutrient quotas
	Enteromorpha sp. object	Macroalgal biomass, productivity and cell nutrient quotas
	Ulva sp. object	Macroalgal biomass, productivity and cell nutrient quotas
	Zostera noltti object	Macrophyte biomass and numbers, cell nutrient quotas and demographic fluxes
	Clams *(Ruditapes decussates)* object	Clam size, biomass, density, filtration, feeding, assimilation and scope for growth

Table 2 – Synthesis of second set of simulations analysed in the present work. A total of 12 simulations were carried out. 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	

Table 3 – Predicted average ebb and flood current velocities and periods at the current meter stations depicted in Fig. 1 for he "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 4 – Summary of time for a 50, 90 and 99% washout of lagoon water and inflow and outflow changes in relation to the validation scenario (see text).

| Scenarios | Variations (%) | | | | | |
| | Washout times | | | Flows | | |
	50%	90%	99%	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

Table 5 – Summary of simulations described in Table 2. 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

Table 6 – 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**
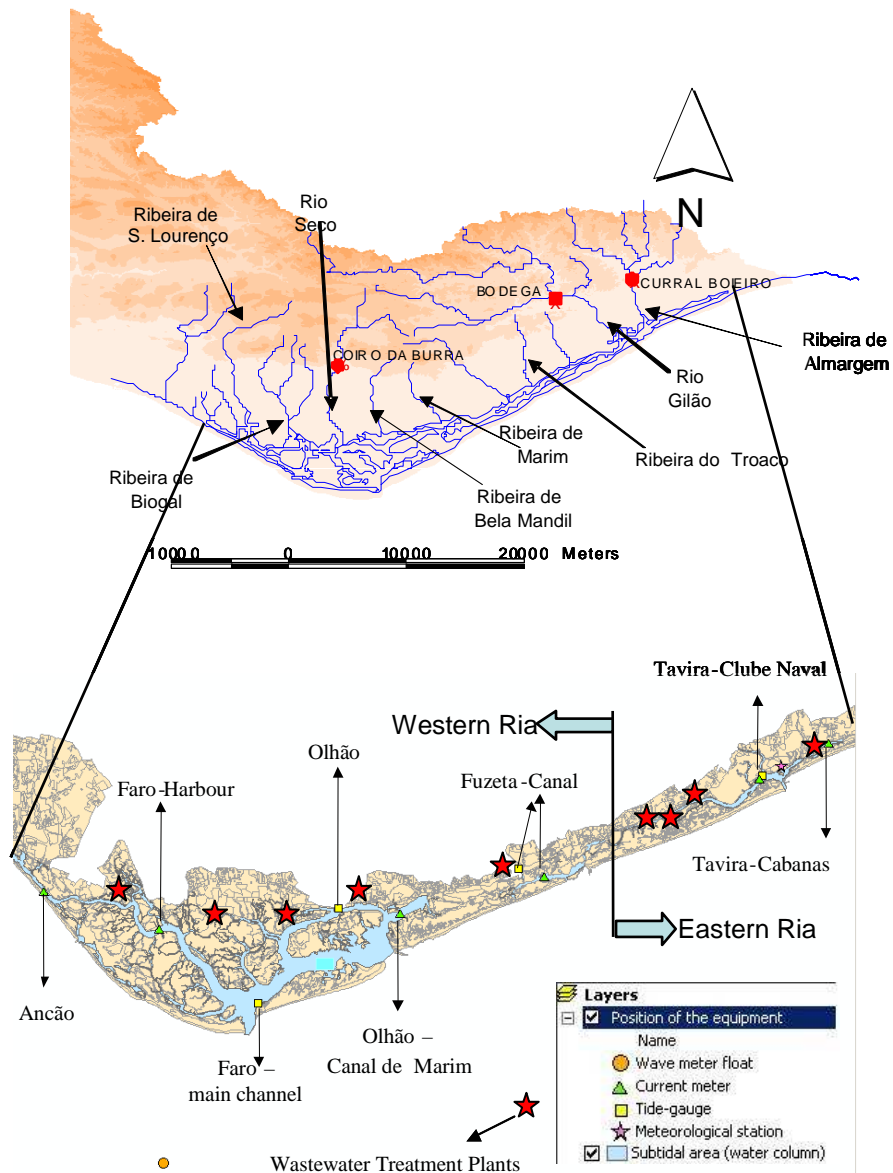
Fig. 1 – GIS image showing Ria Formosa coastal lagoon and its watersheds with stream gauge stations shown as red dots (upper map). Also shown the Location of current meter and tide-gauge stations surveyed by the Portuguese Hydrographic Institute in 2001 (IH, 2001) and used for model calibration (lower and amplified map). The vertical line in the lower image separates the "Western" from the "Eastern" Ria, the former corresponding to the model domain (see text).
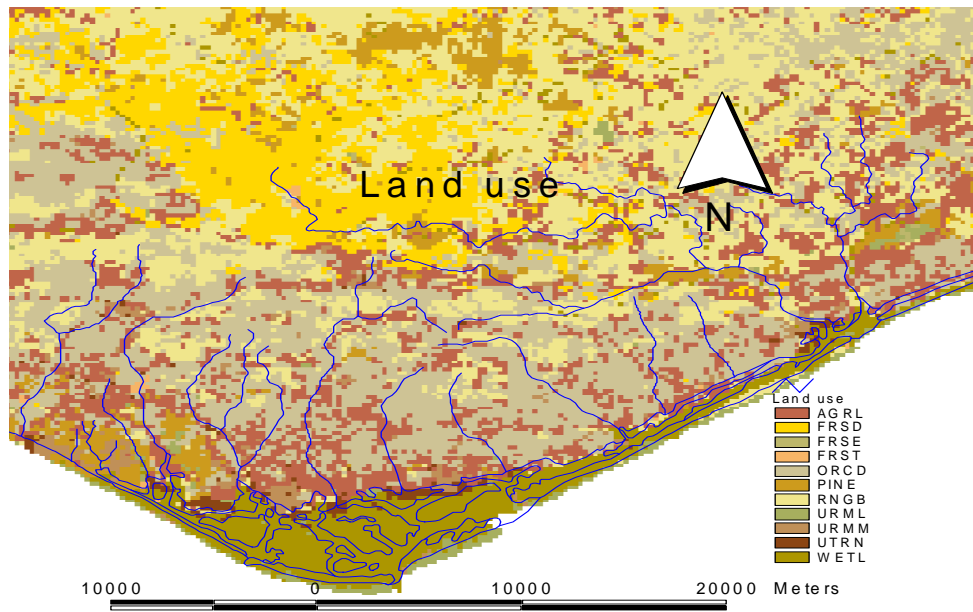
Fig. 2 - Land use in Ria Formosa basin. AGRL - Agricultural Land-Generic; FRSD - Forest-deciduous; FRSE - Forest-evergreen; FRST - Forest-mixed; ORCD – Orchard; PINE – Pine; RNGB - Range-brush; URML - Residential Med/Low Density; URMM - Residential Medium Density; UTRN – Transportation; WETL – Wetlands.
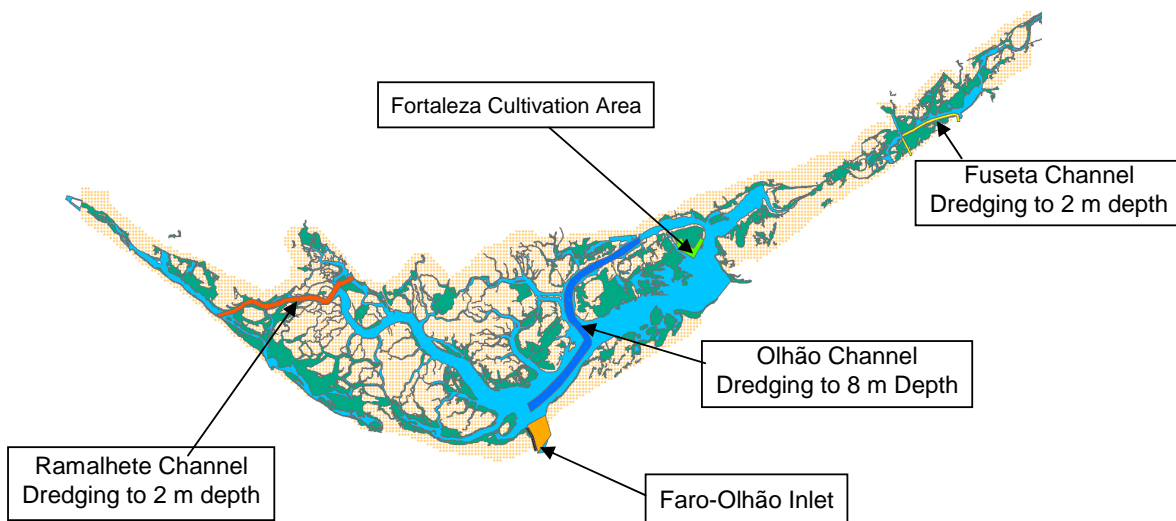
Fig. 3 – Scenario location regarding changes in lagoon bathymetry. In the Ramalhete and Fuzeta scenarios, average depth is increased by c.a. 0.5 m, with the opening of a small new inlet in the latter. In the Olhão channel scenario, depth is increased two fold. The Faro-Olhão scenario corresponds to a significant widening of the inlet. In the Fortaleza scenario, depth is decreased until the hydrographic zero, to simulate sediment accretion - a current practice among bivalve producers of adding sand to their rearing areas, in order to improve sediment quality for bivalve growth.
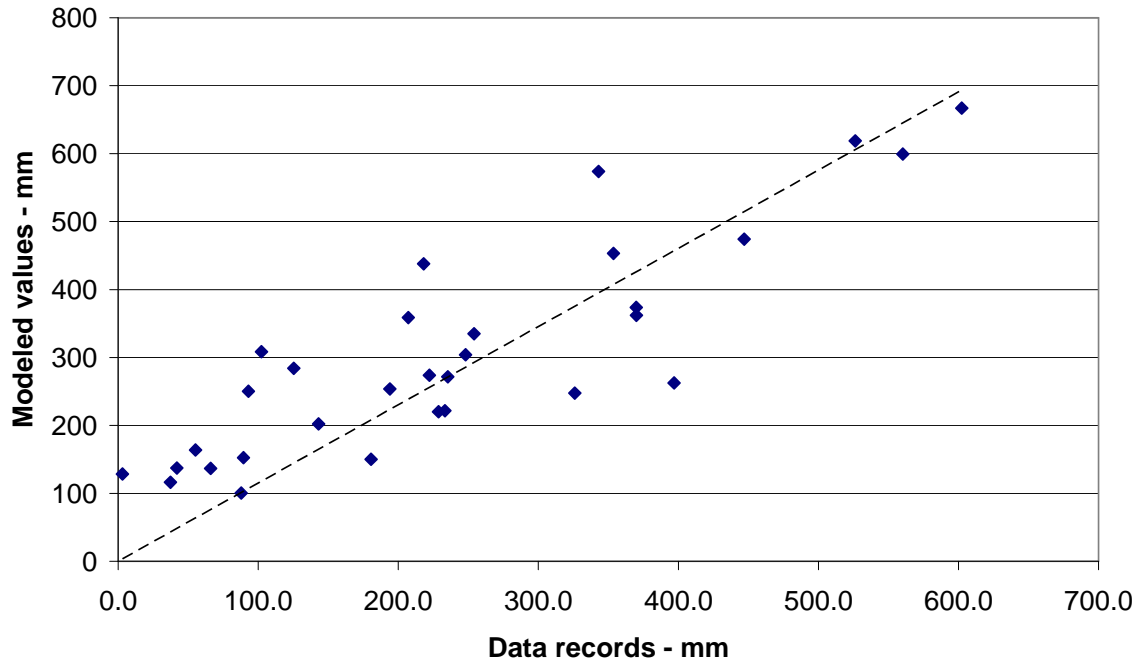
Fig. 4 - Annual flow: Modeled versus measured values.
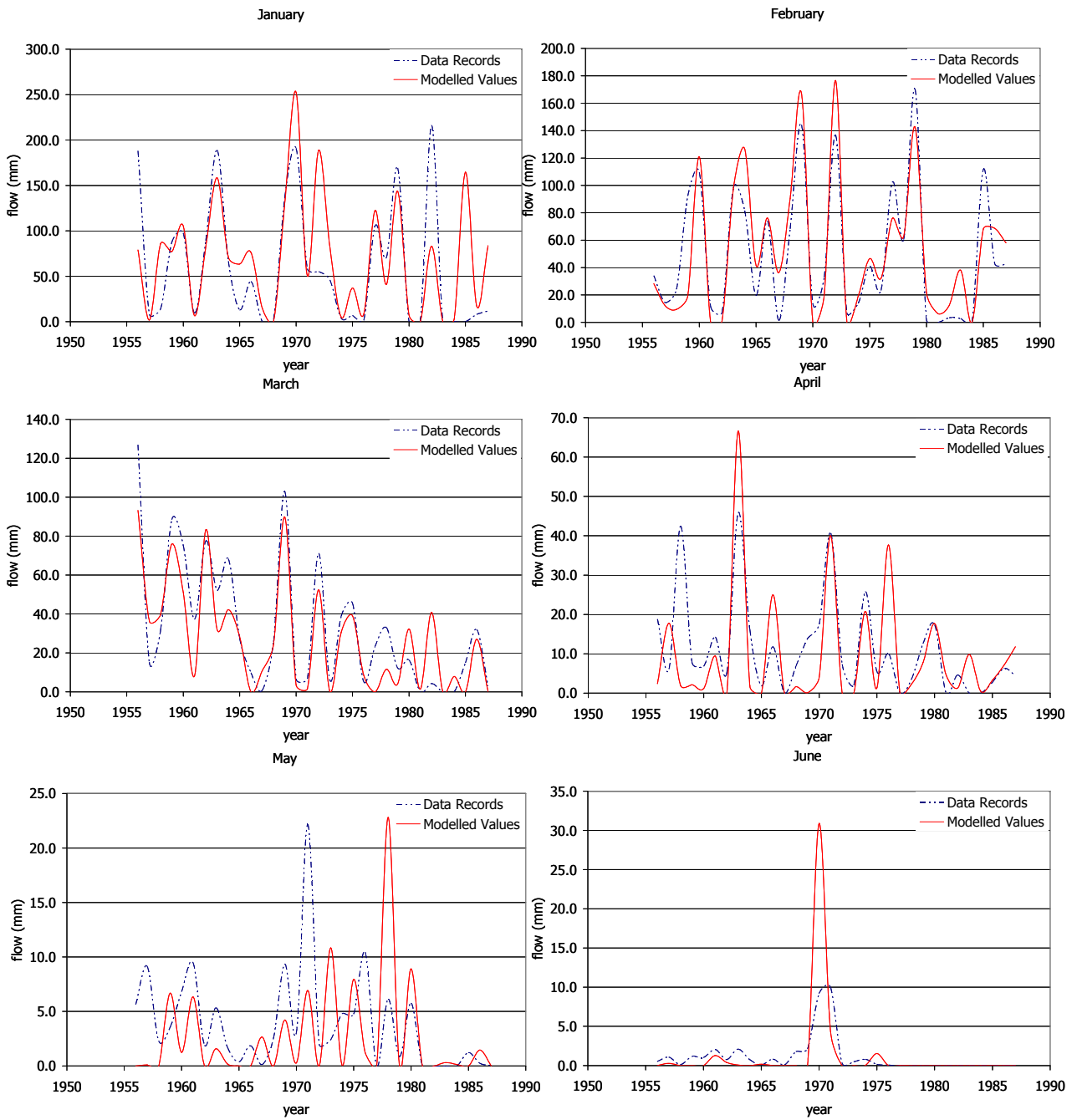
Fig. 5 - Monthly flow: Modeled and measured values from January till June.
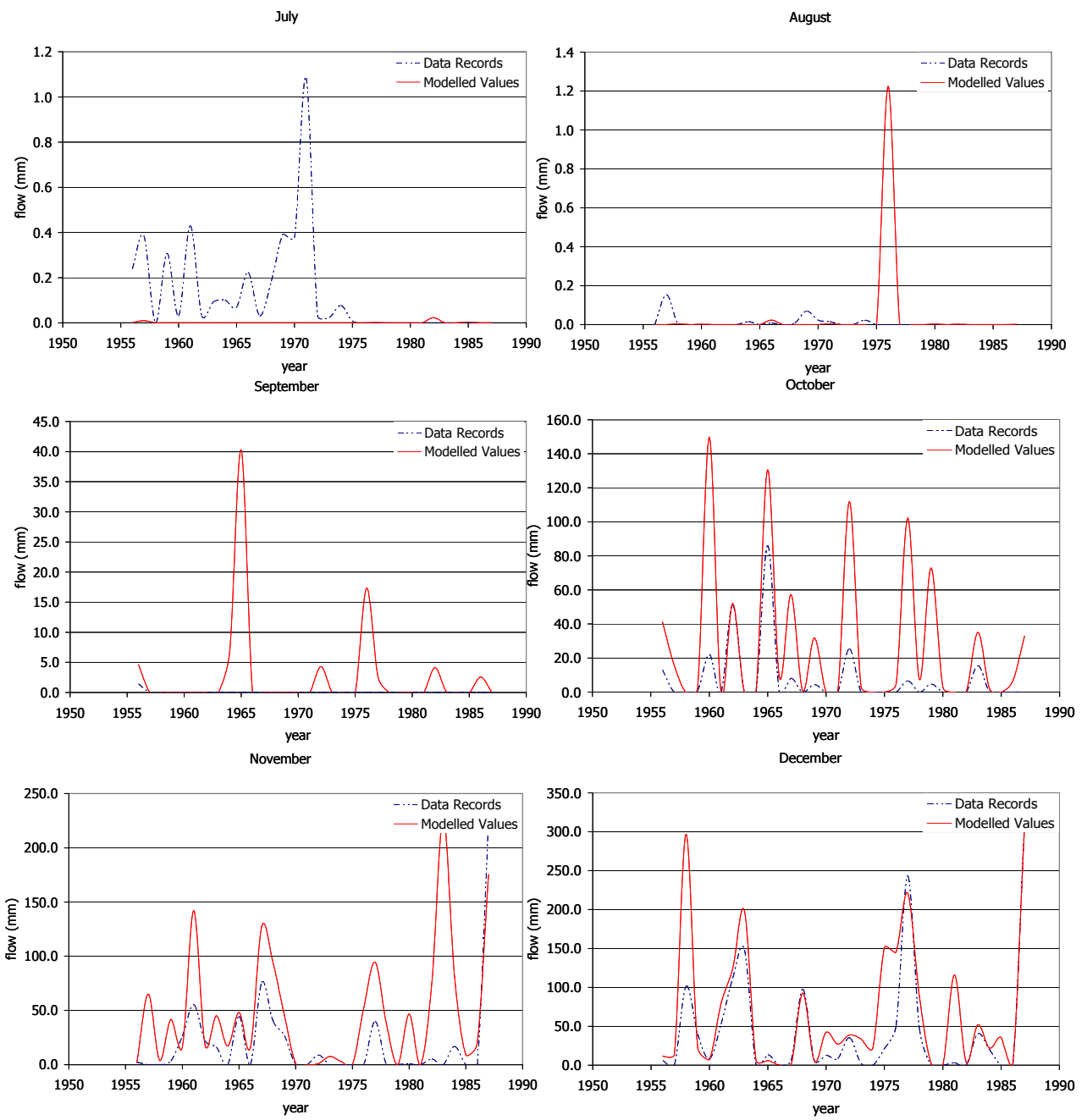
Fig. 6 - Monthly flow: Modeled and measured values, from July till December.
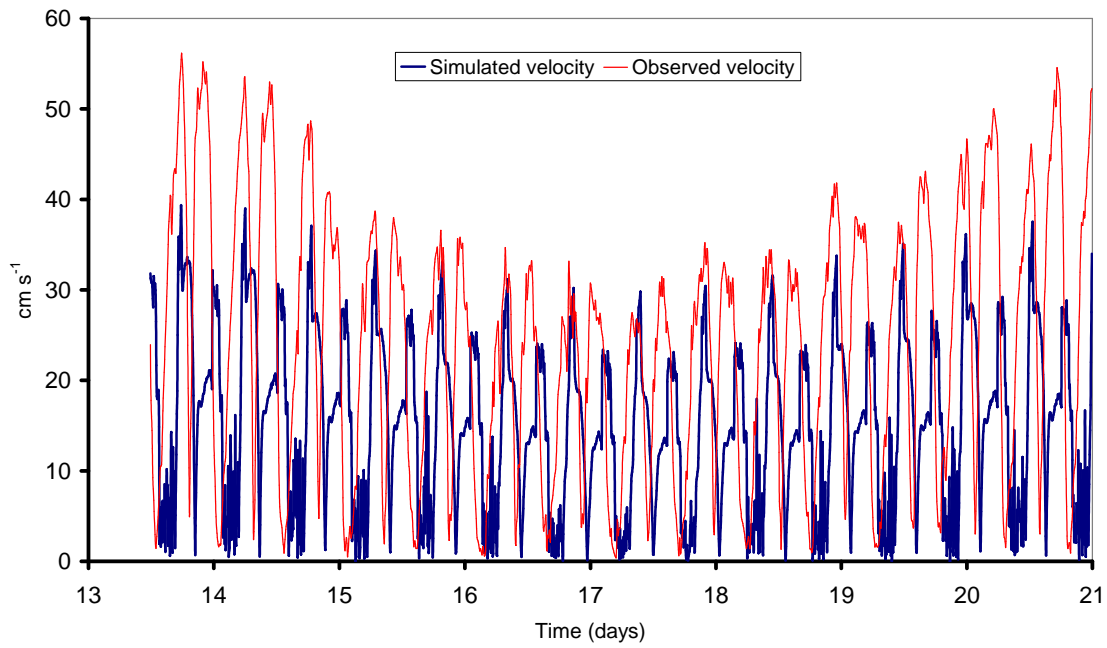
Fig. 7 – Predicted and measured velocities at Ancão (cf. – Fig. 1).
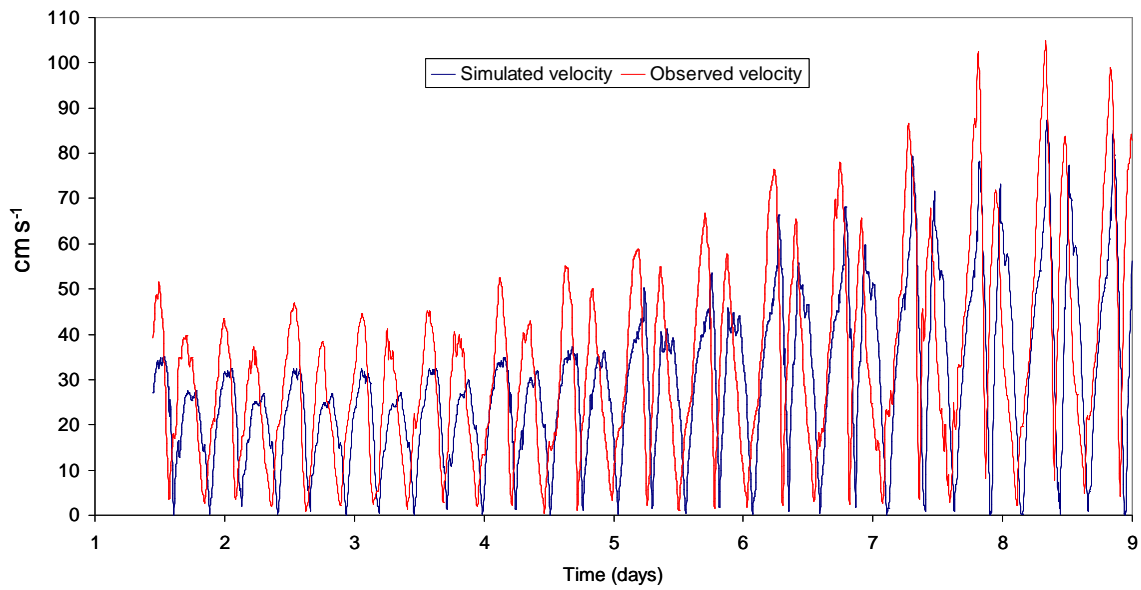
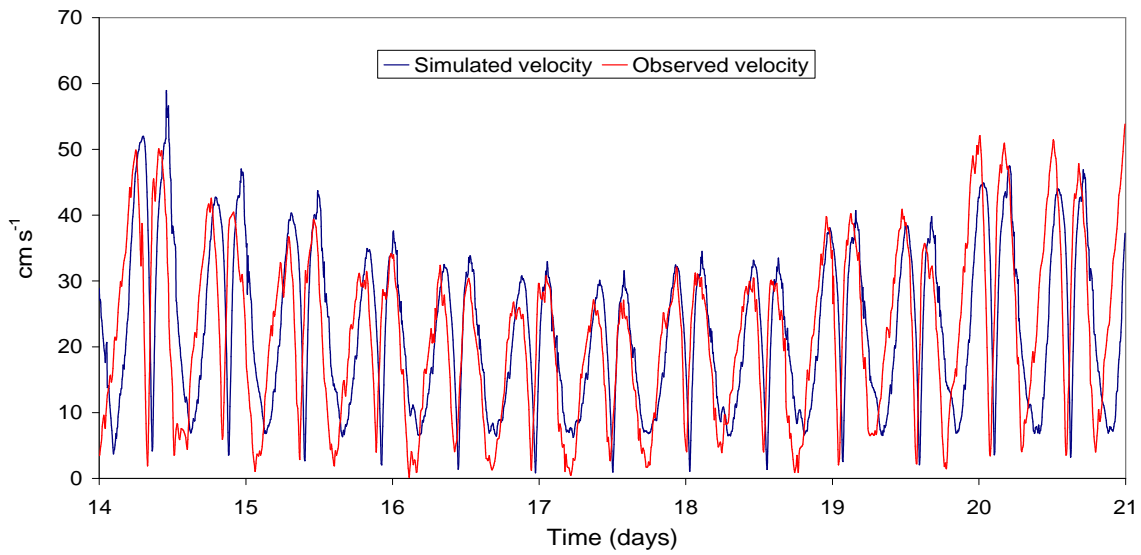Fig. 8 – Predicted and measured velocities at Olhão – Canal de Marim (cf. – Fig. 1).

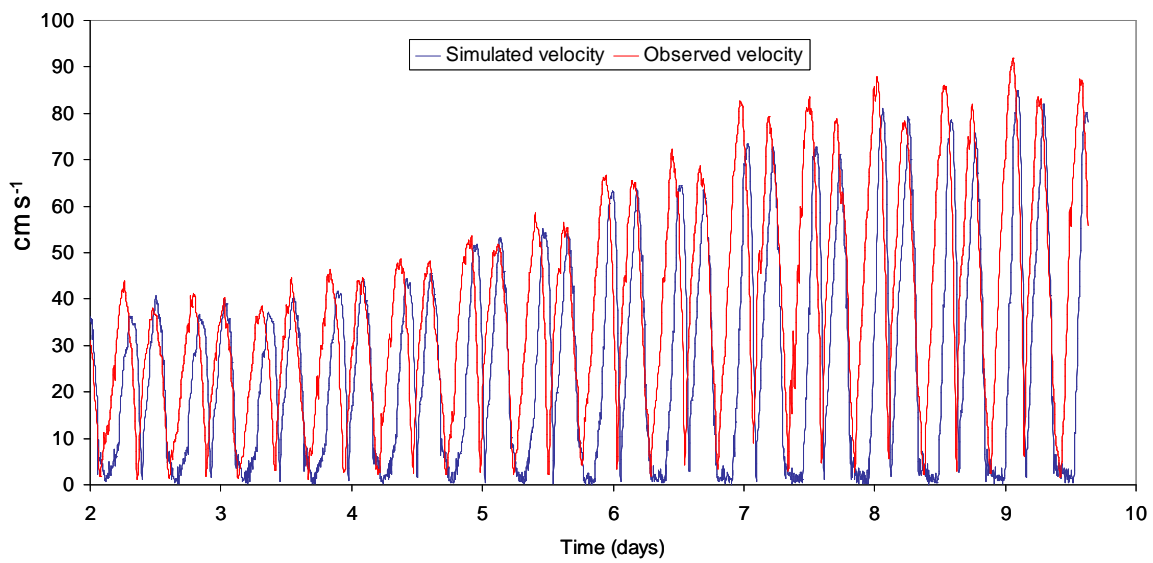Fig. 9 – Predicted and measured velocities at Faro-Harbour (cf. – Fig. 1).

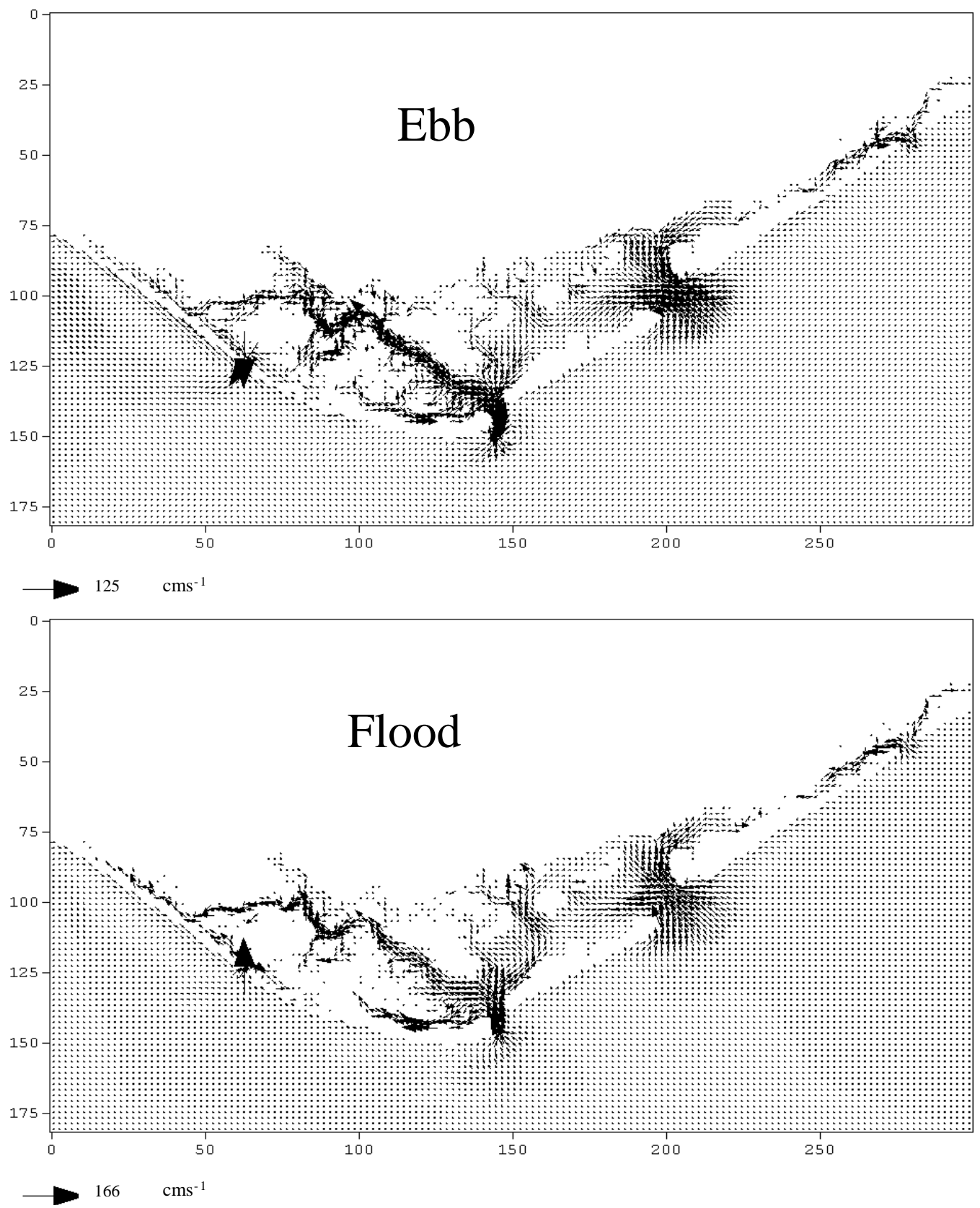Fig. 10 – Predicted and measured velocities at Fuzeta - Canal (cf. – Fig. 1).

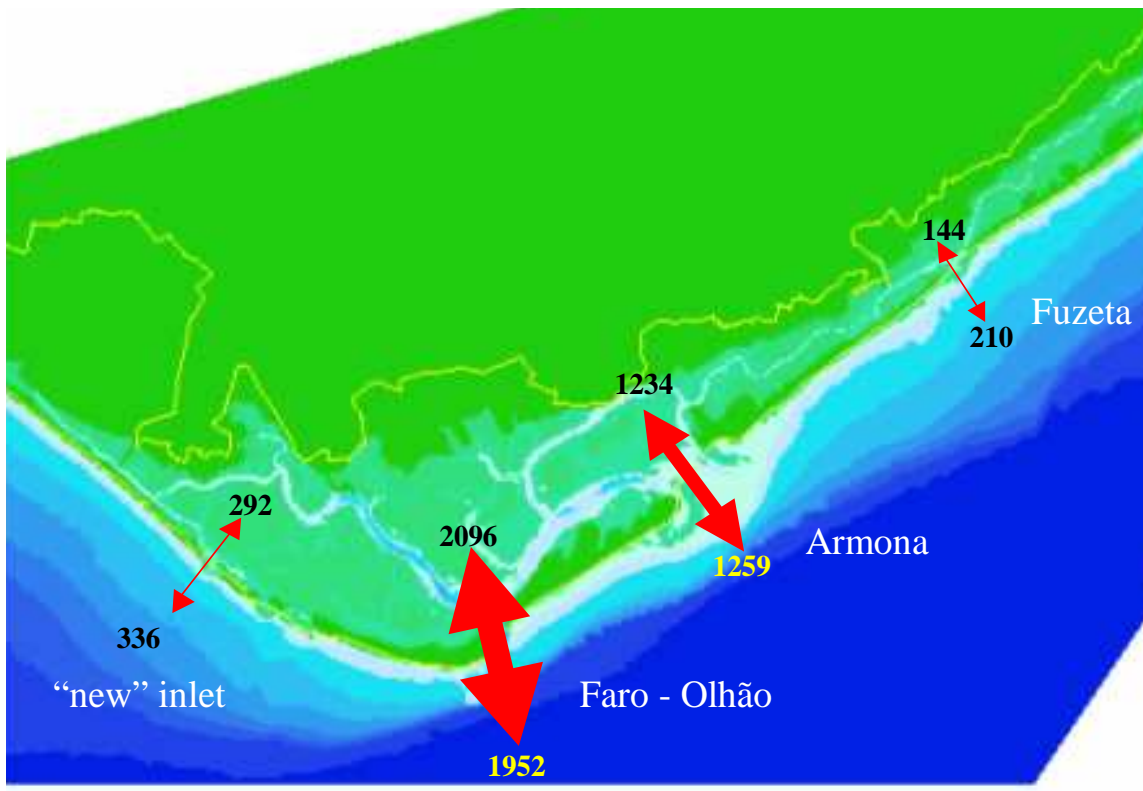Fig. 11 – General circulation patterns during the ebb and during the flood (see text).

Fig. 12 – Averaged inflows and outflows ($m^3 s^{-1}$) through Ria Formosa inlets (see text).
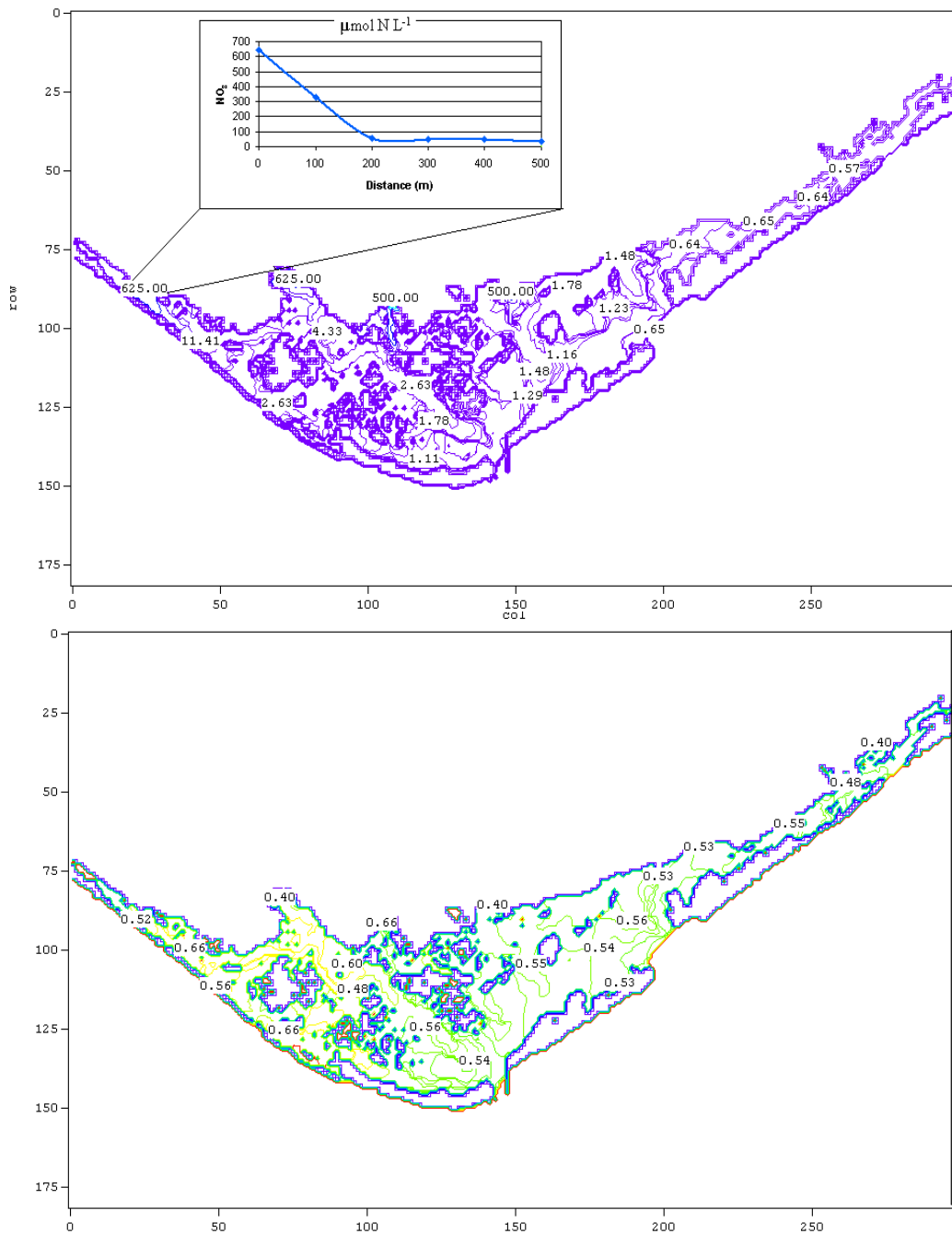
Fig. 13 – Nitrate concentration isolines predicted by the model after simulating a period of 15 days with river and WTP inflows (upper) and without inflows (lower). The plot inserted in the upper figure shows the decrease in nitrate concentration as a function of distance from river mouth, for one of the rivers. Numbers at both axes of the isoline plots refer to model grid line and column numbers (see text).