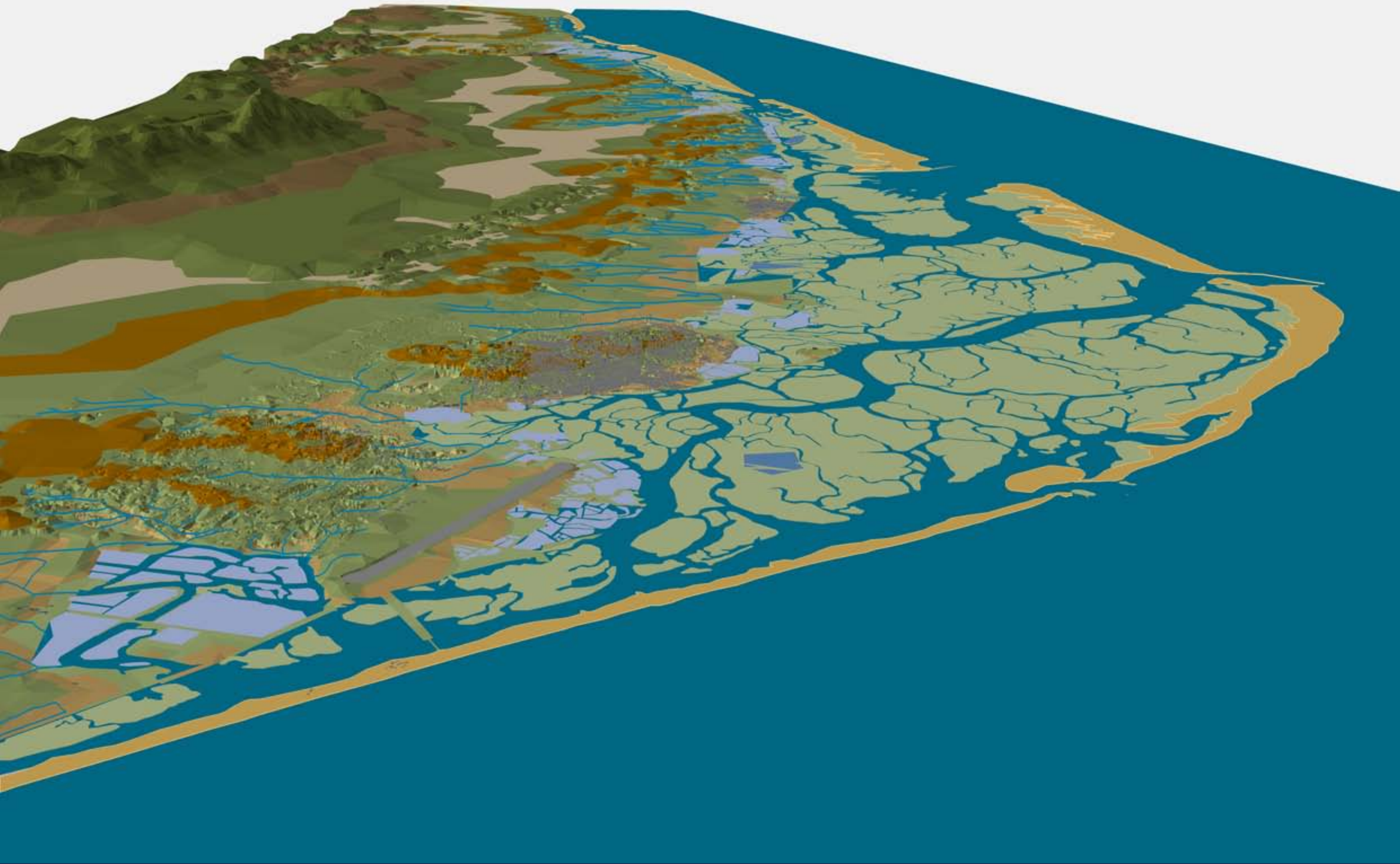

RIA FORMOSA

Challenges of a coastal lagoon in a changing environment

Edited by
Jaime Aníbal, Ana Gomes, Isabel Mendes & Delminda Moura

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UNIVERSIDADE DO ALGARVE
CENTRO DE INVESTIGAÇÃO MARINHA E AMBIENTAL

3. Role of the Ria Formosa inlets on the physical, chemical and biological exchanges with the adjoining ocean

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3.1 What is this Chapter about?

A coastal lagoon is a "shallow coastal water body separated from the ocean by a barrier, connected at least intermittently to the ocean by one or more restricted inlets" (Kjerfve, 1994). Coastal lagoons are typically found along low-lying coastlines, affected by a tidal range < 4 m and generally < 5 m deep (Bird, 1994; Kjerfve,1994).

Coastal lagoons are important ecosystems because these support a wide range of natural services, highly valuable for society. These complex systems provide food, storm protection, tourism, among others. So, they contribute to the overall productivity of coastal waters by sustaining a variety of habitats, including salt marshes, seagrasses, and/or mangroves particularly important for many fish and shellfish species. Water quantity and quality in a lagoon is influenced by the rate at which the lagoon loses or gains water from exchange with the ocean, surface runoff, evaporation, precipitation and groundwater (Allen et al., 1981). Lagoon–ocean exchange is mainly driven by tides, responsible for the lagoon water balance (see Box 3.1.).

Box 3.1. Do you know what tides are?

The tide is a periodic movement of rising and falling of the water resulting from the combination of gravitational attraction forces exerted by the moon and sun on the rotating Earth and the centrifugal forces generated in the Earth's rotation around the centre of mass of the system Earth-Moon-Sun. In addition to the gravitational and centrifugal forces, when we want to study and understand the tide we must consider two additional forces, the Coriolis force which is an inertial force due to the Earth's rotation about its own axis, and the frictional force due to the movement of the water with respect to its boundaries.

The magnitude of tidal inputs and patterns of circulation/hydrodynamics are key physical properties that control the residence time of water and associated compounds (see Box 3.2.). Inner areas of the lagoons usually have low flushing rates because of restricted exchange with the ocean. However, close to the inlets the water renewal is promoted, depending on the size and shape of the lagoon, the level of connectivity with the ocean, tidal range, and freshwater flow.

Box 3.2. Did you know what residence time is?

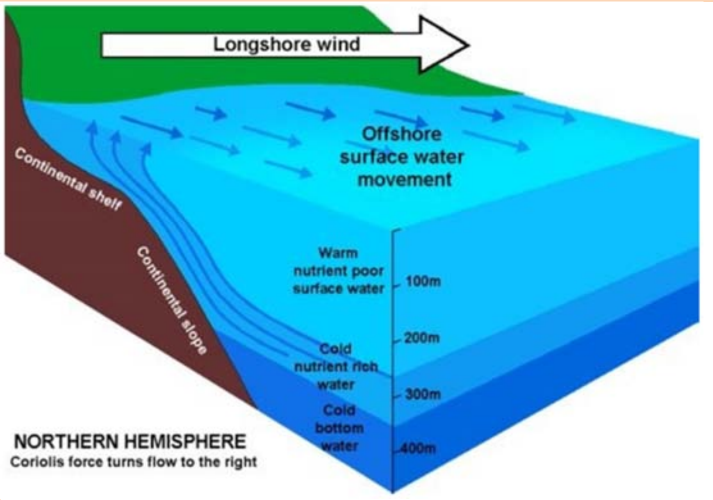
Residence time is the time a particle spends in a reservoir. Residence time is defined as the amount of water in a reservoir divided by either the rate of addition of water to the reservoir or the rate of loss from it. The various reservoirs in the water cycle have different water residence times. The oceans have a water residence time of 3000 to 3230 years; this long residence time reflects the large amount of water in the oceans. In the atmosphere the residence time of water vapour relative to total evaporation is only about 10 days. Lakes, rivers, coastal lagoons, ice, and groundwaters have residence times lying between these two extremes and are highly variable. In the case of a coastal lagoon such as Ria Formosa, the residence time is determined by tidal exchange and is commonly defined as the tidally-averaged time that a Lagrangian particle remains entrained within it.

Coastal lagoons and coastal oceans are closely interconnected ecosystems, where the interplaying processes (physical-chemical-biological) with the ocean are pivotal for the ecosystem functioning. There, water characteristics are not controlled just by tidal cycles and other relevant processes like upwelling (see Box 3.3.), but also remineralisation in water column, benthic-pelagic interaction, land runoff and point wastewater discharges must be considered acting as driving mechanisms in the coastal waters. The availability of nutrients, relative high residence time and light penetration in shallow lagoons lead to a high rate of primary productivity (phytoplankton and aquatic plants) in water column specially between Spring and Autumn seasons (Barbosa, 2010). This leads to an increase of rates of primary production and supports high rates of secondary production compared to other aquatic ecosystems (Nixon, 1995). For the systems where tidal influence is relevant, this play a key role on renewal and circulation of the water in the lagoon contributing to avoid eutrophication processes.

Those processes and driving mechanisms should be understood to gain insights into how present and future changes will affect the behaviour of coastal lagoons, which ultimately affect the society. Regardless the advances on observational programs focused on processes occurring in coastal lagoons, a large gap

Box 3.3. Do you know what is coastal upwelling and why is it important?

Coastal upwelling is an oceanographic phenomenon that involves wind-driven motion of dense, cooler, deeper and usually nutrient-rich water towards the ocean surface (Figure below), in response to winds blowing parallel to the coast, more frequent towards the equator, replacing the warmer, usually nutrient-depleted surface water. This process induces a surface current and a water mass transport – Ekman transport - respectively at 45^0 and 90^0 to the right of the wind in the North Hemisphere (left in the South Hemisphere). The offshore directed movement of surface waters leads to the lowering of the sea level along the coast. The nutrient-rich upwelled water stimulates the growth and reproduction of primary producers such as phytoplankton. Due to the biomass of phytoplankton and presence of cool water in these regions, upwelling zones can be identified by cool sea surface temperatures (SST) and high concentrations of chlorophyll *a*.



Conceptual explanation of coastal upwelling in the northern hemisphere (source: http://www.seos-project.eu/modules/oceancurrents/oceancurrents-c04-s01-p01.html; accessed 23 October 2018).

still exists to quantify exchanges, interactions and dynamics between these environments and adjoining ocean. Coupling multidisciplinary data acquired from observations and remote sensing is fundamental to better understand the functioning of these ecosystems.

In the Ria Formosa, the most important coastal lagoon in the south of Portugal, like in other similar systems, the water and

Box 3.4 - Do you know what mass exchanges /transport mean?

Systems can exchange a physical property between them across a boundary. When a system such as Ria Formosa exchanges water mass with the adjacent ocean through an open boundary such as one of the tidal inlets, this exchange can be quantified through a quantity called mass transport whose units in the International System are kg/s. Dividing the mass transport by the density of the water we obtain the volume transport, with units in m^3/s. In confined flows such as in rivers, channels or tidal inlets the volume transport can be called discharge. Moreover, in a water flow if we know the concentration of a given dissolved compound and suspended particles in the water we can calculate the mass transport of these compounds by the flow.

mass exchanges/transport (see Box 3.4.) derive primarily from interaction with the ocean, through the tidal influence, and channel morphology inside the Ria. The geomorphological characteristics of the Ria Formosa, are presented in section 3.2. Information about the tidal signal and tidal prims (see Box 3.5.) at the main inlets and their influence and contribution for the water circulation of the western sector is described in section 3.3, at spring and neap tidal conditions (see Box 3.6.). The sampling strategy to understand the hydrodynamics and characterise the water quality at the main inlets are reported in section 3.4. The main patterns of variability at the three inlets of the western sector, on high and low water, for nutrients and chlorophyll *a* (a proxy of the phytoplankton growth) during the Autumn season in 2011 under a spring tidal cycle (when the variability is maximum) is shown in section 3.5. The role of lagoon-seawater exchanges through the main inlet of Ria Formosa, the Faro-Olhão inlet, on nutrients, chlorophyll and suspended solids in Autumn 2012, at neap and spring tides, as well as the effect of upwelling on it and consequence upon phytoplankton development, in this shallow system, where nutrients and light are easily available is addressed in section 3.6. The final section 3.7 emphasises those dynamic features that makes the Ria Formosa a peculiar, productive system and one of the most important lagoons in Portugal. Here, is presented for the first time the exchanges through the three inlets of the western sector, promoted in a specific temporal "window", in 2012, under upwelling during the Spring season. This corresponds to a period when the phytoplankton development generally increases and during spring tidal conditions when the exchanges are maximum.

Box 3.5. What does tidal signal and tidal prism mean?

In a record of a seawater property such as the sea level, the tidal signal corresponds to the variability due to the various tidal harmonics. The tidal prism of an estuary or lagoon is the volume of water between the surface levels of high tide and low tide. We can distinguish between the flood prism, the volume of water flowing from the ocean into the estuary or lagoon over the flood period of a semi-diurnal tide, and the ebb prism, the volume of water flowing out of the estuary or lagoon, into the ocean, over the ebb period of a semi-diurnal tide. The difference between the flood and ebb tidal prisms of a semi-diurnal tidal cycle is the residual tidal prism or net transport of water.

Box 3.6. Do you know the importance of spring and neap tides?

Spring tides are semidiurnal tides of increased range, which occur approximately twice a month, near the time of new and full moon, when the moon is in syzygy (when the moon, earth and sun are in line). Neap tides are tides of small range occurring between spring tides, near the time of the first and last lunar quarters, when the moon is in quadrature. The fortnightly modulation in semidiurnal tidal amplitudes is due to the various combinations of lunar and solar semidiurnal tides. At spring tides the lunar and solar forces combine together, but at neap tides the lunar and solar forces are out of phase and tend to cancel. In practice the observed spring and neap tides lag the maximum and minimum of the tidal forces, usually by one or two days. In tidal inlets connecting coastal lagoons to the sea and estuaries spring tides have associated stronger tidal currents and neap tides have associated weaker tidal currents.

3.2. Geographic context and morphology of the Ria Formosa Lagoon

The Ria Formosa is a shallow coastal lagoon system, with a triangular shape, of about 100 km^2, 55 km long, with 6 km of maximum width and an average depth less than 2 m, located in the south coast of Portugal (Fig. 3.1). It is a mesotidal system with a mean tidal range of approximately 2 m, varying from 1.5 m to 3.5 m. Ria Formosa is dominated by the semi-diurnal component of the tide and has six permanent connections to the ocean (Ancão, Faro-Olhão, Armona, Fuseta, Tavira and Cacela), which provide a great water renewal. These six inlets delimit three hydrodynamically distinct sectors: the eastern sector that includes Cacela; the central sector that includes Fuseta and Tavira inlets; and the western sector that is the most important one in terms of water circulation, encompassing Ancão, Faro-Olhão and Armona inlets. The Ria Formosa is well-mixed vertically due to reduced freshwater inputs and predominance of the tidal forcing in the water circulation inside it (Cravo et al., 2014).

The western sector of Ria Formosa represents approximately 90% of the total tidal prism of the entire lagoon (Pacheco et al., 2010). This sector includes three inlets (Fig. 3.1), the Ancão inlet at the western flank of the barrier system, the Faro-Olhão and Armona inlets at the eastern flank of this sector and several channels and creeks. The two main channels of this sector are the Faro channel connecting the Faro-Olhão inlet to the city of Faro and the Olhão channel connecting the same inlet to the city of Olhão.

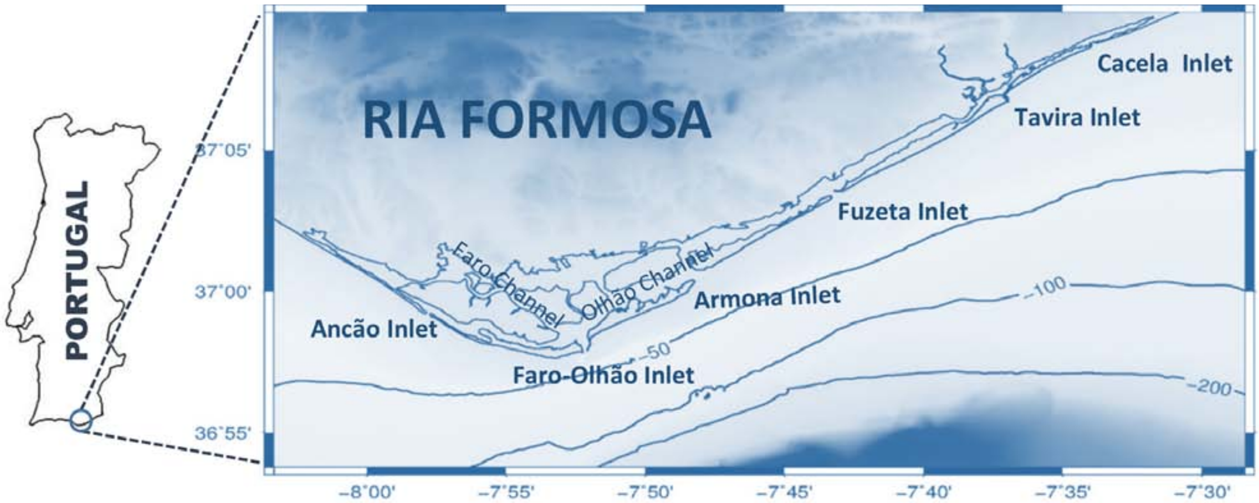


Figure 3.1.
Ria Formosa lagoon location and its western sector with the three main inlets (Ancão, Faro-Olhão and Armona) and the two main channels, Faro and Olhão. Isobathymetric lines of 50, 100 and 200 m deep are also indicated.

The Ancão inlet is a small inlet with a cyclic eastward migration behaviour. The last cycle began after its artificial relocation on 23 June 1997 in a location 3500 m west of its closing position (Vila-Concejo et al., 2003). During this cycle, storm events breached the barrier updrift (2005) and downdrift (2010 and 2015) of the Ancão inlet position, opening a new inlet that competed with the older one for dominance of the tidal prism (Popesso et al., 2016). While in 2005 the new inlet remained open for only three weeks and then closed naturally, in 2010 the new inlet captured a greater volume of the tidal prism and forced the older inlet to close (Popesso et al., 2016). Finally, the new opening of 2015 was still active in November 2015 while the oldest had already closed. The cycle ended in 29 November 2015 with a new relocation of the inlet to a position close to 1997. The relocation was necessary to improve water exchange in the western part of Ria Formosa because in its migration towards the closing position, the Ancão inlet loses hydraulic efficiency, resulting in a decrease of tidal prism.

Faro-Olhão inlet was artificially opened and stabilised with jetties in the period 1929-1955. A consequence of these processes was the capture by this inlet of a large tidal prism from the Armona inlet (Ferreira et al., 2016).

Armona inlet is the only naturally stable inlet of the system (Pilkey et al., 1989). It was the dominant natural inlet in the system, but the evolution of the Faro-Olhão inlet greatly reduced the flow through the Armona inlet resulting in a shift in tidal prism dominance from Armona to Faro-Olhão (Pacheco et al., 2011). Moreover, Armona inlet has been narrowing with time (Pacheco et al., 2010; Fabião et al., 2016) and still now there is no evidence that it stopped.

3.3. Tidal influence on the water circulation of the western sector- spring *vs.* neap tidal conditions

The total tidal prisms for the three inlets of the western sector of Ria Formosa in Autumn of 2011 and Spring of 2012 are compared with those previously obtained in campaigns carried out between 2004 and 2007 by Pacheco et al. (2010), considered as a reference for this study (Fig. 3.2). The total tidal prism of the western sector of Ria Formosa is of the order of 10^8 m^3 in spring tides and decrease to values around 6 x 10^7 m^3 in neap tides. The total tidal prism remains relatively stable over time in spring tides, with oscillations that can be related to the range of the specific tides considered. However, this estimate shows a temporal increase in neap tides, particularly evident in flood conditions. The lowest tidal prisms were estimated in Ancão inlet, in the order of 2-8x10^6 m^3, followed by Armona and Faro-Olhão inlets, in the order of 10^7 m^3 (Fig. 3.2).
From these results is was estimated that Ancão inlet contribution is less than 6% of the total tidal prism in spring and neap tide conditions in both seasons (Jacob et al., 2013; Jacob & Cravo, 2016). Faro-Olhão inlet contributes from 59% to 71% and Armona inlet from 25% to 37%, in neap and spring tide, respectively. These results are in accordance with the previous calculations conducted by Pacheco et al. (2010) some years before. Following the evolution of the relative tidal prisms, the Ancão inlet lost tidal prism in spring tidal conditions to Armona inlet during flood and to both Faro-Olhão and Armona inlets during ebb (Jacob & Cravo, 2016). In neap tidal conditions the tidal prism remained stable in Ancão inlet both during flood and ebb, increased during flood and decreased slightly during ebb in Armona inlet, and increased in Faro-Olhão during flood and ebb.

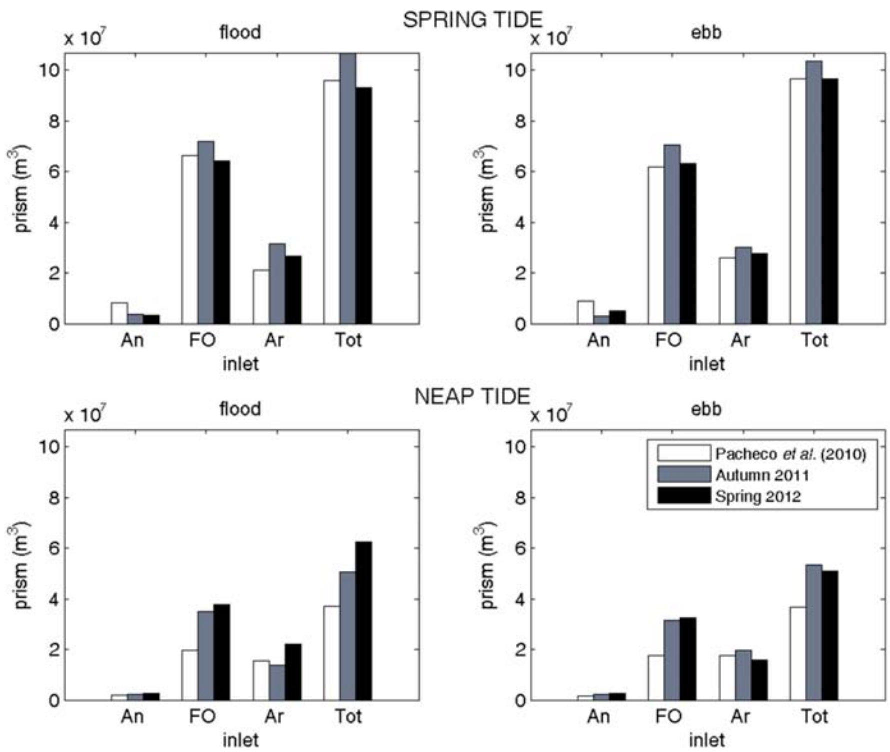


Figure 3.2.
Absolute tidal prisms at the cross sections of the inlets of the western sector of Ria Formosa, An – Ancão inlet, FO – Faro-Olhão inlet and Ar – Armona inlet: results from 2004-2007, considered as reference values from Pacheco et al. (2010) (white bars) in comparison with COALA field experiments, Autumn 2011 (grey bars) and Spring 2012 (black bars).

It is also important to mention that the studied cross-sectional area at Faro-Olhão inlet was much higher than those at the other two inlets of the western sector. During spring tides, when the tidal range is maximum, the sectional area for Faro-Olhão inlet had about 6000 to 6150 m^2, in comparison with 3000 to 3300 m^2 at Armona inlet and 360 to 480 m^2 at Ancão inlet.
The water exchanges between the main inlets of the western sector of Ria Formosa lagoon and the adjoining ocean play a key role on the productivity of both zones also depending on the interconnectivity between them through the main channels as presented in the sections 3.4 and 3.5.

3.4. Sampling strategy to understand the hydrodynamics and to characterize the water quality at the main inlets

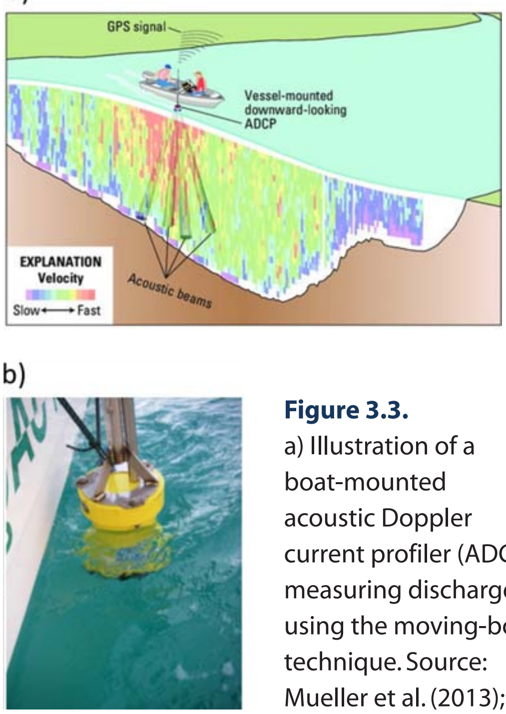
To understand the dynamics of the nutrients and chlorophyll *a* and quantify the exchanges through the main inlets of the western sector several field campaigns along complete tidal cycles were conducted in the last 10 years. The velocity of the currents in the selected sections of the three inlets were measured through an Acoustic Doppler Current Profiler (see Box 3.7.) (Fig. 3.3a), model ADP Sontek, 1500 kHz, bottom track boat mounted (Fig. 3.3b). To quantify the exchanges through the main inlets it was assumed that:

mass transport = concentration of (chemical and biological) parameters × discharge

and discharge represents the water volume transport

water volume transport =velocity normal component × area of the cross section

a)



b)

Figure 3.3. a) Illustration of a boat-mounted acoustic Doppler current profiler (ADCP) measuring discharge using the moving-boat technique. Source: Mueller et al. (2013); b) Exemplification of the ADCP with bottom tracking; side-mounted on the boat used, synchronized with a global positioning system (GPS Garmin GPSMAP 78S) (Photo by J. Jacob, November 2011).

Box 3.7. Do you know what measures an ADCP?

Acoustic current meters utilize the Doppler Effect which is the change in frequency of sound reflected by a moving object to measure the velocity of the currents in moving fluids (Fig. 3.3a). The Acoustic Doppler Current Profiler (ADCP) is an acoustic current meters that emits a beam of sound of known frequency that is reflected in small particles moving with the water. The beam reflected back to the receiver will have a change in frequency proportional to the speed of the particles and thus the current speed. One sound beam will give the component of current in the direction of the beam. However, three orthogonal components are needed to get the true current vector so an ADCP utilizes more than one beam. Four beams are typically used to obtain a redundant velocity measurement for data checking and improved instrument reliability. ADCPs measure water speed at multiple water depths or 'range cells' along the path of the acoustic beams.

To determine the nutrients, chlorophyll *a* and suspended solids concentrations, water samples were collected along the water column (surface, mid water and bottom) using 5 L Niskin Bottles (Fig. 3.4, (see Box 3.8.). Simultaneously, a water characterisation was conducted *in situ* at the same levels of depth along the water column, by using a multiparametric probe (Fig. 3.5) that measures simultaneously temperature, salinity, pH and dissolved oxygen with only one device, through specific sensors.

Box 3.8. Do you know what a Niskin Bottle is?

A Niskin Bottle is a polyvinylchloride (PVC) sampling bottle with water tight closures at top and bottom, used to collect seawater samples for discrete chemical and biological measurements. It is equipped with a subsampling spigot and an air vent and can be triggered at pre-determined depths to collect samples. The PVC material is an unreactive substance, to minimize possible contamination of highly sensitive measurements.

Figure 3.4.
Equipment and use of Niskin Bottle to collect water samples (Photo by J. Jacob, October 2012).

Figure 3.5.
Multiparametric probe used to measure *in situ*: temperature, salinity, pH and dissolved oxygen (in concentration and in percentage of saturation) (Photograph by J. Jacob, December 2011).

Afterwards on the laboratory, the water samples were processed, filtered and kept frozen until further analysis using specific analytical methods (Fig. 3.6).

Figure 3.6.
Laboratorial processing of samples (filtration, Photo by J. Jacob, December 2011) (left) and subsequent analytical procedures to determination of nutrients and chlorophyll *a* concentration (centre and right; Photos by C. Correia, January 2012).

3.5. Variability of nutrients and chlorophyll *a* in spring tidal conditions of Autumn 2011 through the main inlets of the western sector of Ria Formosa

In the last years, several tidal cycles field experiments have been conducted quasi-synoptically at the three inlets on the western sector of Ria Formosa, in the periods of increased phytoplankton activity, i.e. in Spring and Autumn seasons. Here, we present below data for the tidal peaks - low and higher water, on nutrients (Fig. 3.7a) and chlorophyll a (Fig. 3.7b) for the Autumn campaigns of 2011 conducted under a spring tidal cycle, when the differences of water characteristics along the cycle are more evident. Observations of the water quality at low- and high-water during tidal periods of contrasting ranges allow to assess the importance of exchanges between the lagoon and the ocean. The conditions at those periods may be particularly different in Ria Formosa, since the water volume exchanged is large, in the order of 10^7 m^3 in each tidal cycle, as shown in Fig. 3.2 of section 3.3.

The nutrients and chlorophyll *a* concentration (Fig. 3.7), together with measurements taken *in situ* (temperature, salinity, pH and dissolved oxygen; not shown) along the water column of the three inlets showed no significant differences (p>0.05), confirming that the water column is well mixed.
The range of values at the three inlets was similar, with the smallest variability at Faro-Olhão inlet and the highest concentrations at Ancão inlet. The values measured at high tide were relatively uniform and low, while the differences among inlets were more evident at low water of the spring tide. The differences between at high and low water, is illustrative of the dilution effect caused by the incoming of ocean water during the flood period, usually poorer in nutrients than the lagoon water. In each tidal cycle, the highest values obtained at low water reflect clearly the effect of benthic-pelagic processes, as referred in other studies developed in this lagoon (Falcão and Vale, 2003; Newton et al., 2005; Cravo et al., 2013, 2014).
The maximum nutrients concentration observed at Ancão inlet, the smallest and shallowest inlet of the western sector, particularly for nitrate and silicate could be associated with a more intense effect of sediment diffusion and remineralisation. Phosphate at low water is similar between the three inlets, maybe due to its peculiar behaviour, with strong affinity to be adsorbed to the sediments (Falcão and Vale, 1998).

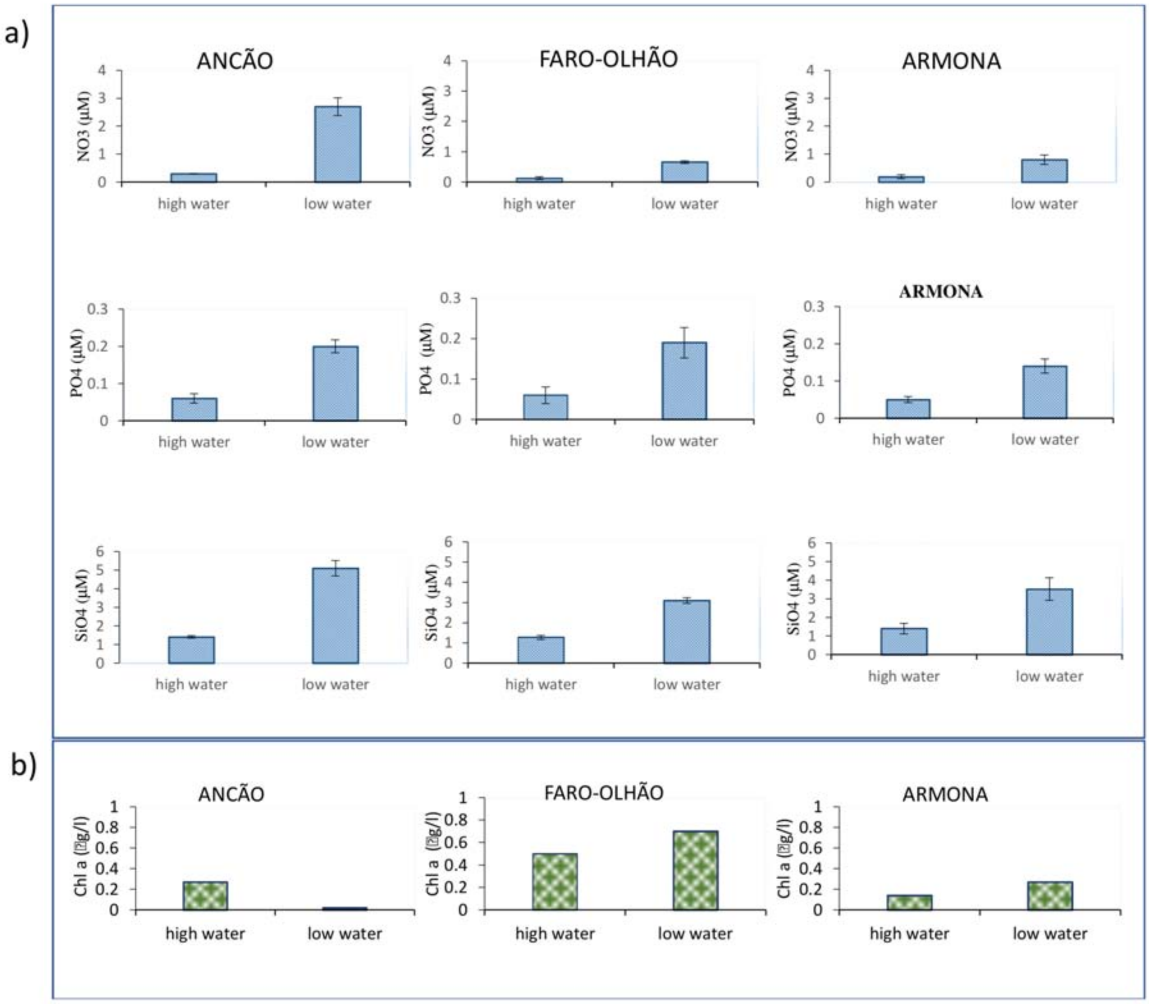


Figure 3.7.
Mean concentration and standard deviation of: a) nitrate-NO3, phosphate-PO4, silicate-SiO4 and b) chlorophyll *a*-Chl a, at high and low water in a spring semidiurnal tidal cycle (22-24 November 2011) at Ancão inlet, Faro-Olhão inlet and Armona inlet.

Chlorophyll *a* was relatively low (< 1 µg/l) and for these tidal conditions the variability among inlets was higher than for the nutrients indicating a less uniform distribution inside the lagoon. The higher mean values at Faro-Olhão inlet could reflect a relatively higher development of phytoplankton, led by a stronger consumption of nutrients at this inlet, as reflected there by the lower nutrients concentration at low water along with possibly more favourable conditions of light and temperature.

3.6 Role of lagoon-seawater exchanges through the main inlet, the Faro-Olhão inlet, at neap and spring tides (Autumn 2012) and the effect of upwelling during spring tide

The interconnectivity between the three inlets of the western sector is possible through their linkage promoted by the main channels and network of secondary ones and creeks. Here, we present data on nutrients (nitrate, phosphate and silicate – Fig. 3.8), chlorophyll *a* and suspended solids (Fig. 3.9), for the main inlet of the western sector of Ria Formosa, Faro Olhão inlet, where the exchanges are the greatest. Data are relative to Autumn 2012, in contrasting tidal conditions - spring and neap tide, particularly for high and low water, when the differences of water characteristics are more evident. It is important to remark that the spring tidal cycle was conducted under an upwelling event, as elucidated latter on. Data for nutrients, chlorophyll *a* and suspended solids, like for temperature, salinity, pH and dissolved oxygen measured *in situ* (not shown) along the water column show that there is no stratification, provided by the well mixed waters, as referred previously in section 3.5.

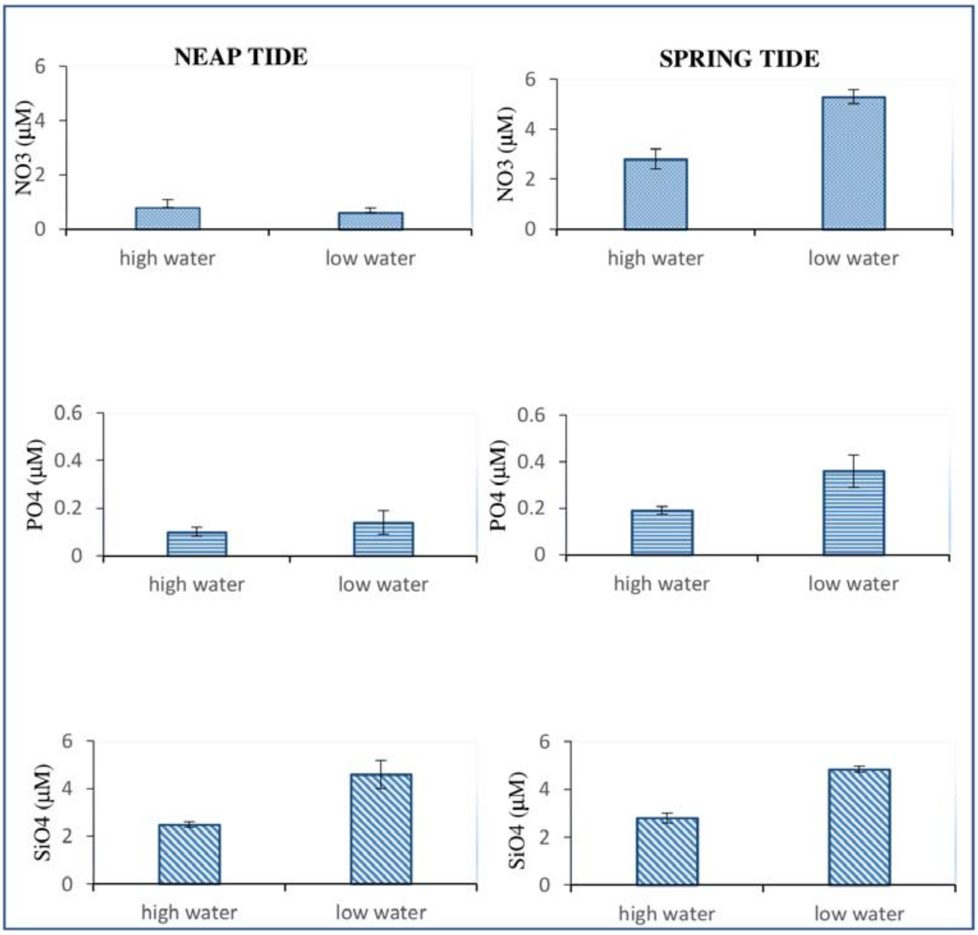


Figure 3.8.
Variability of the mean concentration and standard deviation of nitrate (NO3), phosphate (PO4) and silicate (SiO4) in neap tide (9 October 2012) and spring tide (16 October 2012) at Faro-Olhão inlet during high and low water.

During the spring tidal cycle (Fig. 3.8) the dissolved nutrients presented a notorious contrast between low and high water, pointing to the importance of exchanges between the lagoon and adjoining area, by the calculated tidal prisms at Faro-Olhão inlet (Fig. 3.2), about 9 x10^7 m^3 in spring tide against 6 x10^7 m^3 in neap tide. Nitrate, phosphate and silicate decreased respectively 2 times when the tidal prism was maximum, clearly reflecting their dilution with seawater incoming during the flood of spring tide. Oppositely, in neap tide (Fig. 3.8), when the exchanges were about 30% lower, nitrate and phosphate concentrations were maintained low and similar at both low and high water, while silicates decreased 2 times at high water and reached maximum mean concentrations (4.6 mM) at low water also reflecting the dilution effect. This difference points to the sharp silicate regeneration in sediments and diffused out to water column as shown in other studies conducted in Ria Formosa (Falcão and Vale, 2003; Duarte et al., 2008).

Comparing the mean concentrations of nitrate at neap and spring tide (Fig. 3.8) we found values about four times higher when the lagoon was under maximum oceanic influence (spring tide). This fact may be attributed to the occurrence of a coastal upwelling event during this tidal cycle, that transported an overload of nutrients to the lagoon. In fact, during the spring tidal cycle, at the beginning of the flood phase, nitrate concentrations increased reinforcing that coastal water was enriched in nitrate, as reported in other studies in the Ria Formosa inlets (Falcão and Vale, 2003; Newton et al., 2005), probably due to the nitrification process prevailing there.

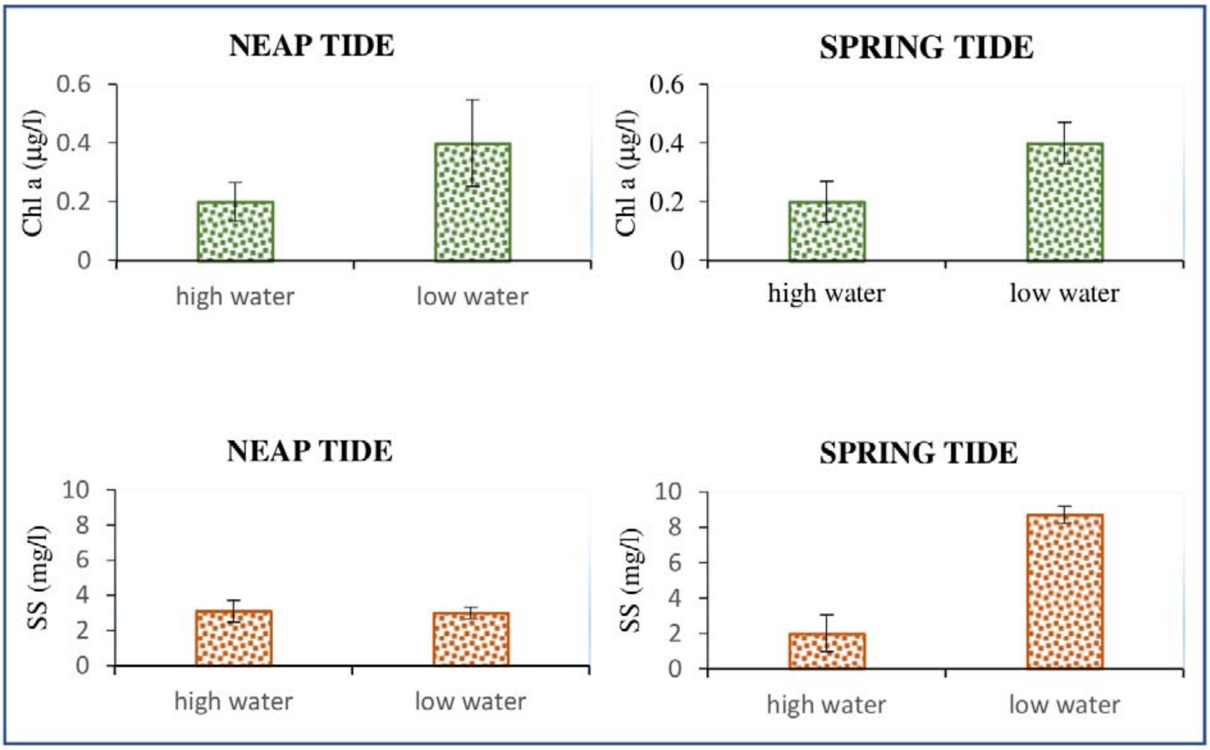


Figure 3.9.
Variability of the mean concentration and standard deviation of chlorophyll a (Chl a) and suspended solids (SS) in neap tide (9 October 2012) and spring tide (16 October 2012) at Faro-Olhão inlet during high and low water.

Chlorophyll *a* was relatively low (mean < 0.5 µg/l) in this Autumn period and similar between both tidal cycles. However, at low water this pigment was 2 times higher (0.4 µg/l) than at high water, suggesting a slight increase of primary productivity inside lagoon when water column is minimum.

An evident increase of suspended particles concentration occurred at low water of spring tide, four times higher than obtained at high water, which may be due to resuspension effect felt during the ebb period, when the currents through the inner lagoon channels may be important. Moreover, this fact suggests that its major source is inside the lagoon and that by dilution effect the concentrations decreased during the flood period, with the incoming coastal water, usually poorer in particulate material.

The pattern of variability of the water characteristics can change temporally, dependent on the hydrodynamics and circulation between this inlet, the channels and the other inlets, internal processes including biological activity or even due to variability of other driving forces associated to environmental conditions like meteorological and oceanographic processes occurring in the adjacent ocean that will affect the inner areas of the Ria Formosa.

In fact, the tidal variability is not the only driving mechanism responsible for the differences between field surveys. There are also other forcing mechanisms to consider namely meteorological/oceanographic drivers. Winds are quite relevant for this issue. Under westerlies, upwelling is a recurrent process that occurs in the south coast of Portugal, more frequently between April and October (Relvas & Barton, 2002). For example, in Autumn of 2012, between the consecutive spring and neap tidal cycles (Figs. 3.8 and 3.9) an upwelling event occurred as reflected in a decrease of sea surface temperature recorded by a sensor coupled to a Pressure Transducer (PT) deployed in a pier at the Deserta Island (Fig. 3.10). This provides information to better understand the processes involved in the Faro-Olhão Inlet.

As can be seen in Fig. 3.10, under a period of prevailing west winds there was an evident decrease of the water temperature (*ca.* 5 °C) accompanied by a decrease of the sea level. Those characteristics are typical of coastal upwelling events. However, it was also observed that after the last campaign the wind relaxed. These conditions will have an insightful signature in the budgets of mass exchanges through the Faro-Olhão inlet, as further described in the following section.

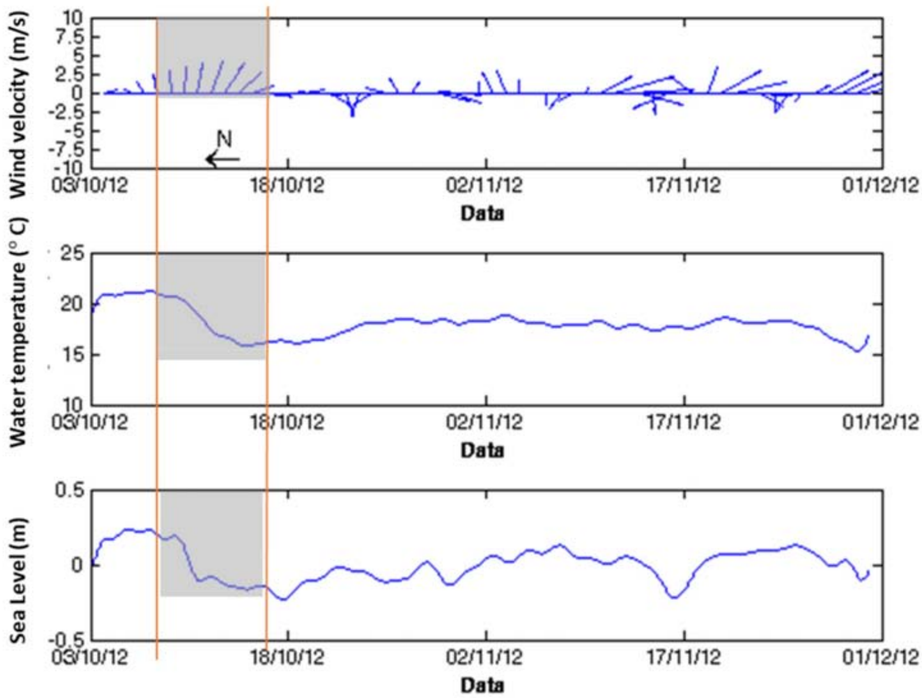


Figure 3.10.

Data acquired by the PT deployed at the Deserta Island pier, in the period between 3 October and 1 December 2012: velocity and direction of the wind from the Faro Airport weather station; water temperature and sea level. N indicates the north direction. The period in between the two surveys is indicated by the grey box, delimited by the two orange lines.

Sea surface temperature (SST) and chlorophyll *a* satellite images (Fig. 3.11) provide and support further information important to understand the water characteristics variability between the consecutive campaigns inside the Ria Formosa that is influenced by the physical-chemical-biological characteristics of the adjacent ocean water. The alterations of the conditions on the adjacent coast will afterwards be reflected inside the Ria Formosa (Fig. 3.10). The SST and chlorophyll *a* satellite images, in the week of the first campaign, in neap tide (9 October) and in the following week, during the second campaign in spring tide (16 October) and some days later on, until 22 of October (Fig. 3.10), show that on the first campaign the sea surface temperature was > 20 °C but before the second campaign an upwelling event occurred and, as recorded in the PT, the sea surface temperature dropped (*ca.* 5 °C). With no wind relaxation (Fig. 3.9) the development of phytoplankton was not relevant and chlorophyll *a* concentration was < 1 µg/l while the nutrients markedly increased (Figs. 3.8 and 3.9). Nevertheless, the satellite image of chlorophyll *a* that cover a period beyond the day of the last survey (until 22 October) confirms that under wind relaxation after the last survey (Fig. 3.9) there was an increase of phytoplankton biomass, reflected in the concentration of chlorophyll *a* (Fig. 3.11).

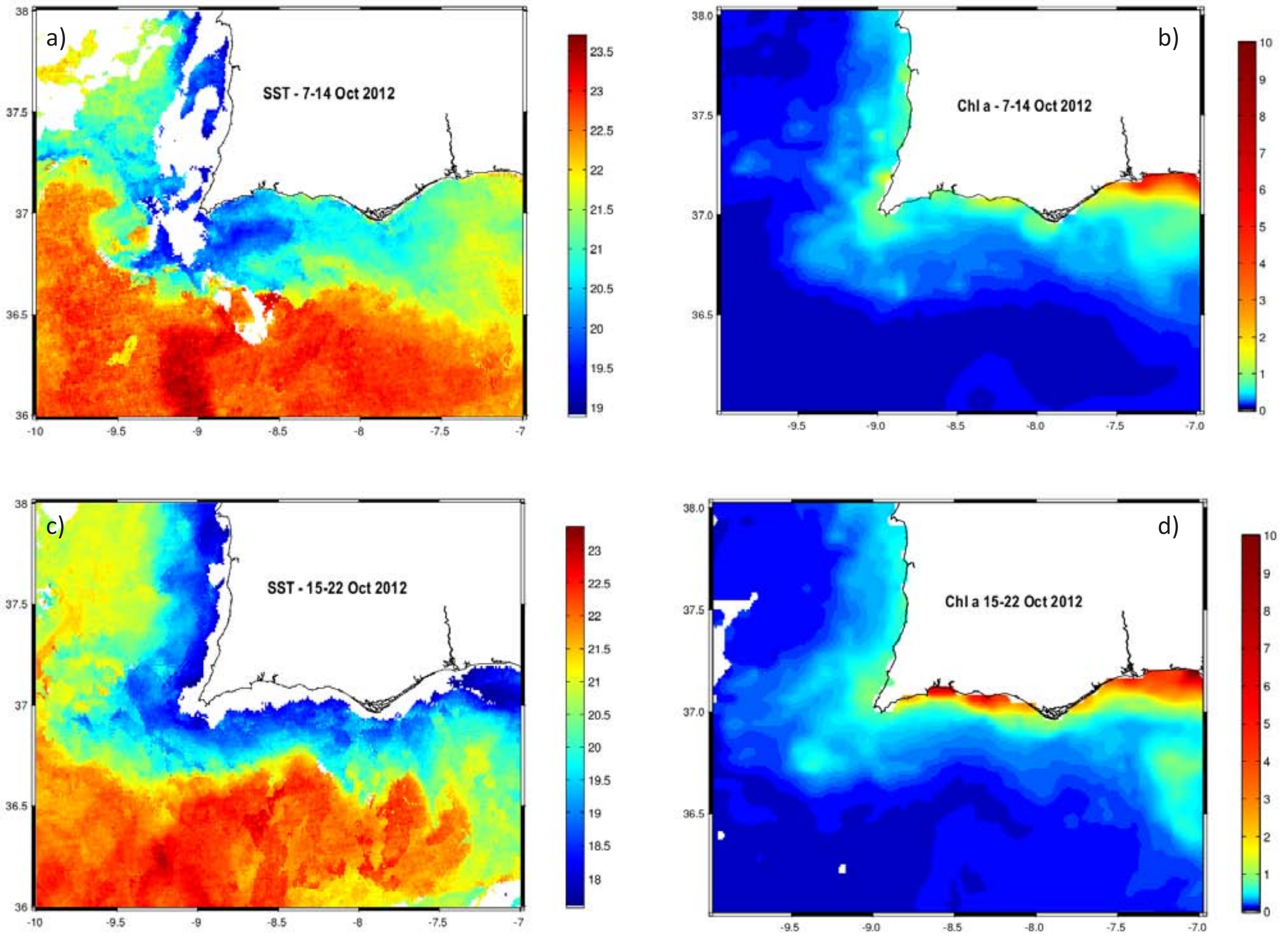


Figure 3.11.
Weekly composite SST and chlorophyll *a* satellite images in the south coast of Portugal, covering the period of the neap (9 October) and spring tide (16 October) for the Autumn 2012 campaigns: a) SST and b) Chlorophyll *a* for 7-14 October, c) SST and d) Chlorophyll *a* for 15-22 October (source: Ocean Color, NASA).

This information helps to understand how these coastal oceanographic processes dominate the variability of the water exchanges through the main inlet, demonstrating their impact on the productivity of Ria Formosa.

In summary, these data show how the interplay of physical-chemical-biological processes control the variability of the characteristics of Ria Formosa. The interconnectivity between the lagoon and the sea does not depend exclusively on tides but also on other driving forces acting on the coast, such as wind and associated oceanographic processes, either inner countercurrent or upwelling. The subsequent phytoplankton development in this shallow system, where nutrients and light are easily available, shows that these are factors playing a key role to comprehend the Ria Formosa dynamics. The variability relies on the intensity, duration and phase of the forcing mechanisms on the area of interconnectivity and interaction between the Ria Formosa and the adjoining coastal zone.

3.7. Mass exchanges promoted in specific temporal "windows". Case of Spring 2012 for spring tidal conditions under upwelling

The Spring period, as representative of the most productive season was selected to depict the magnitude of the mass budgets/exchanges of water, nutrients, chlorophyll *a* and suspended solids through the three main inlets of the western sector of Ria Formosa. Here, we present the case for Spring 2012 considering only spring tidal conditions, when the exchanges are maximum, under an upwelling event. Data for the exchanges of nutrients, chlorophyll *a* and suspended solids through these inlets, promoted during flood and ebb periods, are schematically represented in Fig. 3.12. The corresponding net transports, including water are shown in Table 3.1.

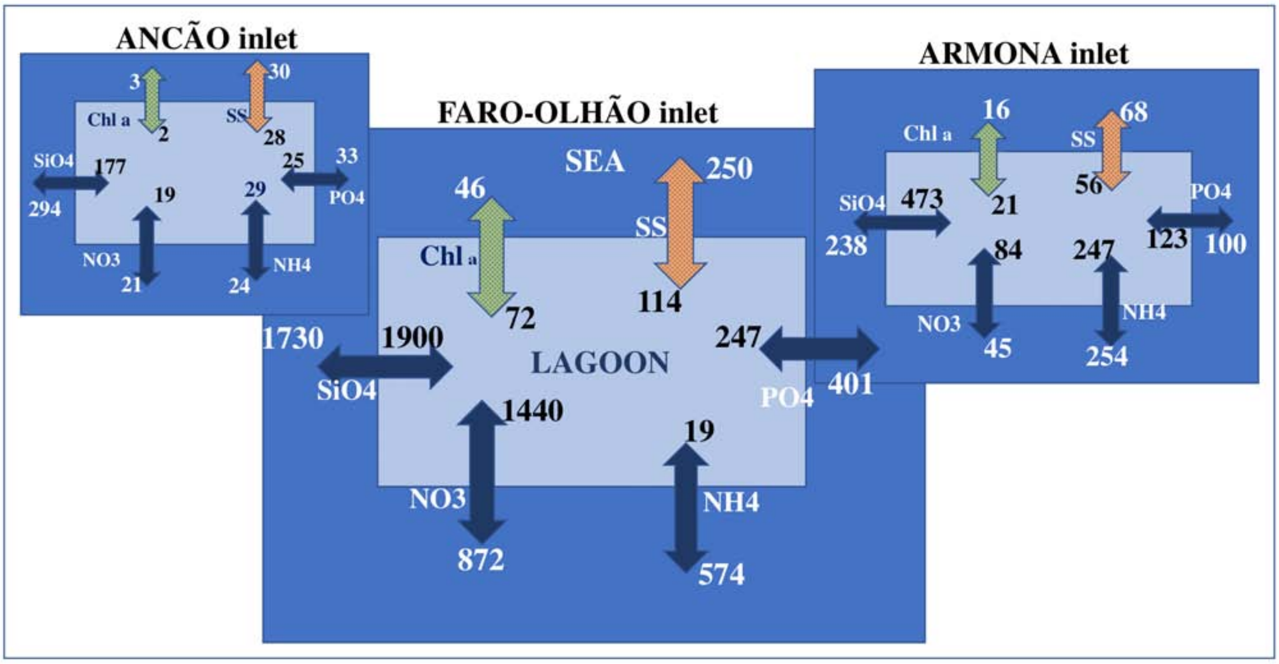


Figure 3.12.
Conceptual representation with arrows for inflows and outflows relative to Chlorophyll *a* (kg) - green, suspended solids (ton) - orange and nutrients (kg) – dark blue, between the three inlets of the western sector of Ria Formosa (lagoon – light blue) and the coastal ocean zone (sea – intermediate blue), in the Spring season of 2012, during the flood and ebb phases of a spring tidal cycle under upwelling. The size of the boxes and of the arrows is not to scale but intend to represent the relative contribution of each of the three inlets for the exchanged material: Faro-Olhão>Armona>Ancão.

The mass budget of nutrients, chlorophyll *a* and suspended solids estimated on the basis of their concentrations and on the discharge of water exchanged in flood and ebb tide, for Ria Formosa in a spring tidal cycle of Spring 2012 (Fig. 3.12) reflects the tidal rhythm of water volume transporting these compounds through the three inlets (Ancão, Faro-Olhão and Armona inlets). It is important to remark that this sampling period was conducted after a coastal upwelling event, when the coastal water is enriched in nutrients and chlorophyll *a*. This may explain the mass transport of these compounds much higher in flood than in the ebb period, particularly at the Faro-Olhão inlet. During the flood high amounts of nitrate import (1.4 ton) were estimated, denoting the nitrification process, on the well mixed and oxygenated coastal waters, along with an import of chlorophyll *a* (72 kg). As previously confirmed by the satellite images, after upwelling events there is an increase of phytoplankton growth, as expressed by the chlorophyll *a* concentration (Fig. 3.11). However, the ammonium, phosphate and suspended solids were higher in the ebb period than during the flood, suggesting that the internal processes (remineralisation, bioturbation, sediments diffusion and resuspension) inside the lagoon are pivotal and prevail even during the upwelling occurrence, providing a net export of these compounds (555 kg, 127 kg and 136 ton, respectively, Table 3.1) to the coastal area.

Table 3.1. Net water prism and mass exchanges of chlorophyll *a*, silicate, phosphate, nitrate, ammonium and suspended solids for the three inlets of the western sector of Ria Formosa: Ancão (AN); Faro-Olhão (FO) and Armona (AR), in the Spring season of 2012 during a spring tidal cycle, considering the flood and ebb phases. Positive values indicate import into the Ria Formosa and negative values export from the Ria Formosa

Date	Inlet	Water prism (m^3)	Chlorophyll *a* (kg)	Silicate - Si (kg)	Phosphate - P (kg)	Nitrate - N (kg)	Ammonium - N (kg)	Suspended Solids (ton)
21-03-12	AR	1.21E+06	5	235	23	39	-7	-12
22-03-12	FO	4.47E+06	26	170	-127	572	-555	-136
23-03-12	AN	-1.56E+06	-1	-117	-8	-2	5	-2

Comparing the three inlets, the exchanges of nutrients, chlorophyll *a* and suspended solids were 1-2 orders of magnitude higher through Faro-Olhão inlet than in the other two inlets. This fact may be explained by the larger and deeper section of Faro-Olhão inlet, reflected by its maximum sectional area as indicated in section 3.3. There, the water volume transported is about 2 times higher than the volume transported through Armona inlet and about 20 times higher than through Ancão inlet, the smallest and shallowest inlet from the western sector of the lagoon.
As this upwelling situation can occur episodically, it can be predicted an import of nutrients and chlorophyll *a* from the coastal area into the lagoon during those periods that will contribute to stimulate the productivity along all the trophic chain.

3.8. Lessons learned from the role of the Ria Formosa inlets on the mass exchanges with the adjoining ocean

Ria Formosa is a complex system, highly variable in different time scales. The behaviour of the three inlets could change over time, owing to tidal ranges variability, changes in the patterns of circulation and hydrodynamics, due to the interconnectivity between the inlets and their main channels, shifts in meteorological and environmental conditions and coastal processes in the adjoining ocean, like the episodic events of upwelling portrayed in both conditions of Autumn 2011 and Spring 2012.

The tidal effects felt within the Ria Formosa coupled with upwelling pulses could import material from the coastal ocean able to further fertilize this system, setting up its biological productivity particularly in the Spring season. However, by internal processes coupling pelagic-benthic interactions, Ria Formosa, generally, exports material (nutrients and suspended solids that include organic matter) mainly through the Faro-Olhão inlet, contributing to fertilise and increase the biological productivity of the adjoining ocean.

Acknowledgements

The authors would like to thank all the technical staff and collaborators of COALA campaigns, as well as the logistic support of Captains of Faro and Olhão Ports.

This work was funded by the Portuguese Foundation for Science and Technology (Fundação para a Ciência e Tecnologia, FCT) through the project ref.: PTDC/MAR/114217/2009-COALA".

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