

# Nutrients and particulate matter exchanges through the Ria Formosa coastal lagoon, Portugal

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## ABSTRACT

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The Ria Formosa lagoon (south coast of Portugal) is a highly productive shallow mesotidal system of high water renewal through six permanent connections to the ocean. The three inlets in the western sector represent ~ 90% of the total tidal prism. To understand spatial and temporal dynamics of nutrients, chlorophyll a (proxy of phytoplankton) and particulate matter, data acquisition of these parameters along with current velocity was conducted hourly during two consecutive semi-diurnal spring and neap tidal cycles (~12.5 h) in the three inlets of Ria Formosa western sector, in late autumn of 2011. In all three inlets, nutrients ranges were typical for this time of the year, varying in antiphase relative to tidal signal, although less evident during the neap tide. Chlorophyll a and suspended solids concentrations were lower during the neap tidal cycle with less evident tidal variation than for nutrients. Net transport results show that Ria Formosa plays an important role in the mass export of nutrients to the adjacent coastal area, particularly during spring tides, with a greater contribution by the Faro-Olhão inlet, followed by the Armona and Ancão inlets. These two, regardless of the residual tidal prism, export nutrients while suspended solids were imported. The Faro-Olhão inlet presented different behaviour: it acts as a flood dominated inlet importing chlorophyll a and nitrate, and exporting ammonium and suspended solids. Nonetheless, values can change due to tidal variability, asymmetry and distortion, and interconnection of inlets inside the lagoon. To further understand the seasonal variation of this system more surveys will be conducted.

**ADDITIONAL INDEX WORDS:** tidal inlets, tidal prism, spring and neap tides, transport, chlorophyll a, suspended solids

## INTRODUCTION

Coastal lagoons are usually highly productive systems of ecological and economic importance to communities. Such is the case of Ria Formosa, a National Park in the south coast of Portugal of internationally recognized environmental importance (Natura 2000 and Ramsar Convention). With an area of approximately 80 km<sup>2</sup> (55 km long, 6 km at its widest point), this lagoon system is shallow (average depth <2 m) and mesotidal (mean tidal amplitude ~2 m, 1.5-3.5 m) with semidiurnal tides (Newton and Mudge, 2003). Daily water renewal is high ranging from 80x10<sup>6</sup> m<sup>3</sup> during neap tides to 150x10<sup>6</sup> m<sup>3</sup> during spring tides (Neves et al., 1994) with a water exchange rate of around 75% in each tide (Tett et al., 2003). The lagoon is well mixed vertically, with no evidence of persistent haline or thermal stratification due to reduced freshwater inputs (restricted to the Gilão River discharging in Tavira) (Newton and Mudge, 2003).

This highly dynamic and multi-inlet barrier island system comprises five islands and two peninsulas, separated by six tidal inlets; the barrier islands protect a large embayment of salt marshes, sand flats and a complex network of natural and partially dredged channels (Barbosa, 2010; Pacheco et al. 2010).

Hydrodynamically, the lagoon may be divided into three sub-embayments: the western, that includes the Ancão, Faro-Olhão and Armona inlets, the central, comprising the Fuzeta and Tavira inlets, and the eastern embayment, that includes the Lacém inlet (Barbosa, 2010). Water circulation inside the lagoon is mostly driven by tidal forcing and tidal exchanges occur predominantly through the Faro-Olhão and the Armona inlets (Salles et al. 2005; Pacheco et al., 2010). In fact, the inlets in the western sector alone account for c. 90% of the total water volume exchanged semi-diurnally whereas the central and the eastern embayments together transmit only c. 10% of the total tidal prism during both spring and neap-tides (Pacheco et al., 2010). Therefore, to understand mass exchanges between the Ria Formosa lagoon and the ocean, this study focused on the western inlet system (Figure 1).

The Ancão inlet is the westernmost inlet of the Ria Formosa and was artificially relocated (June 1997, 3.5 km west of its previous position) to improve water circulation between the lagoon and the adjacent ocean. It is a small ebb-dominated inlet with both tidal and wave-dominated characteristics and cyclic eastward migration behaviour (Vila-Concejo et al., 2004). During spring tides it is reported to account for c. 8% of the total flow, but during neap-tides the tidal prism in this inlet is of reduced importance (Pacheco et al., 2010). The Faro-Olhão inlet is the main one in terms of water exchanges (Pacheco et al., 2010); it was artificially and progressively opened between 1929 and 1955 and stabilised with

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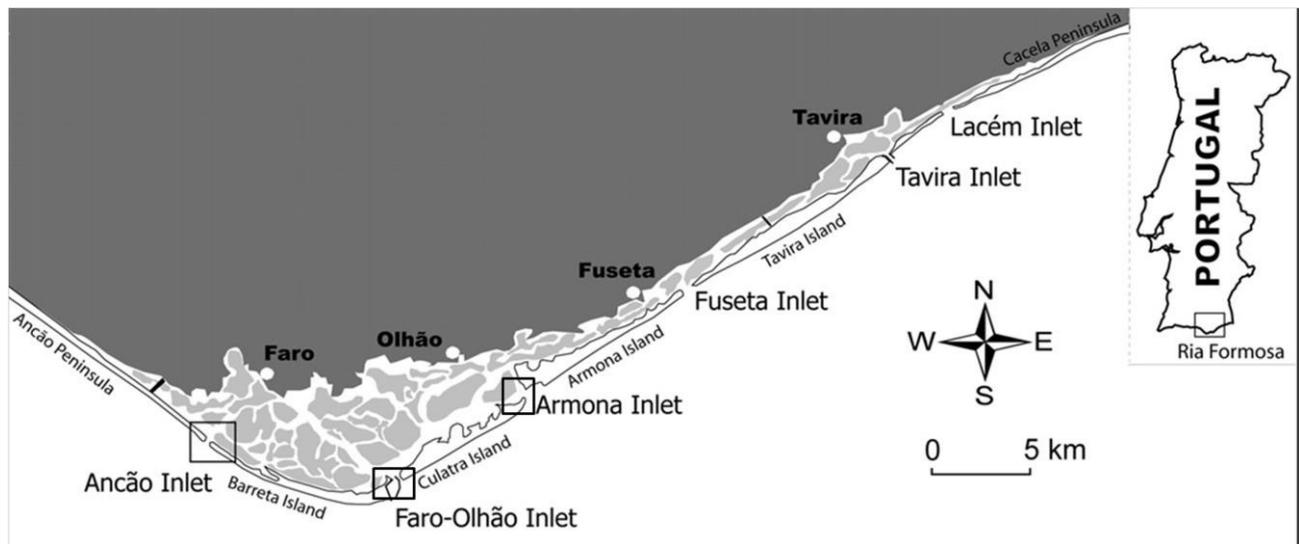


Figure 1. Inlets location within the western sub-embayment of the Ria Formosa lagoon: the Ancão, Faro-Olhão and Armona inlets (adapted from Pacheco et al., 2011).

two jetties. Its opening intended to maintain navigable depths in the channel leading to the urban centres Faro and Olhão (Pacheco et al., 2008). It is always flood-dominated and reported to trap c. 61% of the total tidal prism during spring tide and c. 45% during neap-tide (Pacheco et al., 2008, 2010). The Armona inlet is a natural inlet of stable location, formerly the dominant inlet in the system. A large part of its tidal prism has been captured by the Faro-Olhão inlet since its opening; nevertheless these inlets are hydrodynamically connected, enhancing the Armona inlet flushing capacity. This ebb dominated inlet, during spring tide is reported to account for c. 23% of the total flow and during neap-tides the tidal prism is shared in similar proportion with the Faro-Olhão inlet (c. 40%) (Pacheco et al., 2008, 2010). These three inlets of the western sub-embayment of the Ria Formosa lagoon show a clear circulation pattern at spring tide, in which the excess flood prism at the Faro-Olhão inlet ebbs through the Ancão and the Armona inlets. During neap-tides this connection is reduced because the adjacent channels are too shallow (Pacheco et al., 2010).

In coastal lagoons with a permanent connection to the sea the tidal effect is marked and consequently chemical characterization of the system is mainly regulated by tidal exchanges at the ocean boundaries. Hence, concentrations of nutrients and other compounds in the lagoon strongly depend on the variability of the water quality of the adjacent coastal waters (Alcântara et al., 2012). Additionally, tidal exchanges are important for limiting the impacts of nutrients (Newton and Icely, 2004). The above mentioned inlets are well characterised in hydrodynamic and morphodynamic terms, but information regarding chemical mass exchanges during tidal cycles is limited. Some studies have tackled the importance of lagoon-sea water exchanges on the biological productivity of Ria Formosa in terms of nutrients and chlorophyll *a* (Newton et al., 2003; Falcão and Vale, 2003; Newton and Mudge, 2005) but were based on samplings at fixed stations inside the lagoon that did not consider the mass transport of these compounds. To our knowledge only two studies have approached the nutrient and chlorophyll *a* transport through two inlets of the Ria Formosa, the Ancão inlet (Alcântara et al., 2012) and the Faro-Olhão Inlet (Cravo et al., 2012). A major

understanding of the net mass transport of nutrients and particulate matter through the three inlets of the western system has never been considered and this study intends to fulfil that gap of knowledge. The goal of this study was to characterise concentrations and calculate the net mass flow of nutrients, chlorophyll *a* (as a proxy of phytoplankton activity) and particulate solids through the western inlets system in autumn conditions over two complete semi-diurnal tidal cycles during spring and neap-tides (consecutive fortnightly tidal extremes).

## METHODS

### Field sites and campaigns

This study focused on the Ancão, Faro-Olhão and Armona inlets of the western sub-embayment of the Ria Formosa lagoon (Figure 1). Field measurements were performed in late autumn conditions (2011), over two complete semidiurnal tidal cycles (~12.5 h) during consecutive spring-tide (ST) and neap-tide (NT). Flow velocity was measured every hour during the entire semidiurnal tidal cycle along the cross-section of each inlet (Figure 1) using a Sontek/YSI 1.5-MHz Current Surveyor Acoustic Doppler Profiler (ADP) with bottom tracking, side-mounted on a boat. Temperature (T), salinity (S), pH and dissolved oxygen (DO in concentration and in % saturation) were measured in situ using a YSI 6600 XL multi-parametric probe and water samplings were carried out hourly, at the central point of the section, throughout the water column at three depths (surface, Secchi disk extinction depth and bottom, max. 13 m). This central point was selected since in previous surveys for the three inlets no significant differences ( $p > 0.05$ ) in the water characteristics were found horizontally along the cross section (in the middle and extremes). Water samples were collected to determine nutrients (ammonium, nitrite, nitrate, phosphate and silicate), suspended solids (SS) and chlorophyll *a* (Chl *a*) concentrations, using a 5 L Niskin bottle.

### Analysis

Water samples (1 L) for nutrient analysis (ammonium,  $\text{NH}_4^+$ , nitrite,  $\text{NO}_2^-$ , nitrate,  $\text{NO}_3^-$ , phosphate,  $\text{PO}_4^{3-}$ , and silicate,  $\text{SiO}_4^{4-}$ )

were filtered through decontaminated and weighed membrane filters (0.45  $\mu\text{m}$ , for SS determination) and then frozen at  $-20^\circ\text{C}$ . For chlorophyll a concentrations, 1 L water samples were filtered using GF/F glass fibre filters which were frozen at  $-20^\circ\text{C}$  until analysis. Nutrients and Chl a were spectrophotometrically determined by methods described in Grasshoff et al. (1983) and Lorenzen (1967) respectively, while SS were determined through gravimetric methods described in APHA (2002). Detection limits for nutrient determination were: 0.1  $\mu\text{M}$  for  $\text{NH}_4^+$ , 0.05  $\mu\text{M}$  for  $\text{NO}_2^- + \text{NO}_3^-$ , 0.02  $\mu\text{M}$  for  $\text{PO}_4^{3-}$  and 0.05  $\mu\text{M}$  for  $\text{SiO}_4^{4-}$ . The Marine Nutrient Standards Kit (OSIL) was used as reference to ensure accuracy, which was high (relative error lower than 2.5%). Precision was estimated as  $\pm 1\%$  for  $\text{SiO}_4^{4-}$  and  $\text{PO}_4^{3-}$  and  $\pm 2\%$  for  $\text{NO}_3^-$ .

The discharge was calculated through the integration of the product between the velocity component normal to cross-section and the corresponding cross-sectional area. Numerical integration in the time domain of the hourly discharge values during the flood and ebb periods provided the flood and ebb tidal prisms respectively. The residual tidal prism or net transport of water was obtained as the difference between the flood and ebb tidal prisms. The transport of nutrients, Chl a and SS was calculated hourly over the entire tidal cycle multiplying the discharge (Q) by the cross-sectional average concentration. Finally, the net transport of nutrients, SS and chlorophyll a was obtained by integrating in the time domain the hourly transport values over the entire tidal cycle.

### Statistical Treatment

A T-test and ANOVA were applied followed by a Posthoc Tukey pair-wise multiple comparison test to determine if there were significant differences in nutrients, SS and Chl a concentrations along the selected depths as well as between sites. The minimum level of confidence considered was 95 %.

## RESULTS AND DISCUSSION

At tidal peaks (high water - HW and low water -LW), flow velocities for the three inlets were  $\sim 0$  m/s. The maximum values were achieved around mid tide, as typically found in inlets (Duarte et al., 2008). At spring tide, the maximum velocity was  $\sim 1$  m/s, decreasing during neap tide to a maximum of  $\sim 0.5$  m/s.

Physical-chemical data recorded in situ in the three inlets showed different water characteristics between tidal cycles. In the spring tide, water temperature (15.5-19  $^\circ\text{C}$ ) was relatively higher than during neap tide (15-17.5  $^\circ\text{C}$ ) due to the temporal delay between surveys and influence of the air temperature decrease. Salinity (mostly  $\sim 36$  ‰) was relatively lower during spring tide (34.5-36) than in the neap tide (35.3-36.2), associated with a period of rainfall in the Ancão Inlet, during the ebb period. Values of pH varied within a narrow range: 8.0-8.3, typical of coastal waters. A similar temporal variation was observed for the dissolved oxygen, with values varying close to saturation (95-120%). The ranges of these parameters measured in situ were typical for this system in this time of the year (Falcão and Vale, 2003; Newton and Mudge, 2003; Barbosa, 2010).

Concentrations of total inorganic nitrogen – TIN (ammonium+nitrate+nitrite), phosphate, silicate (not shown by its similarity with the other two nutrients) and SS (not shown) throughout the water column showed no significant differences ( $p > 0.05$ ), confirming that the water column is well mixed. Hence, values presented are the mean concentrations at the three depths during spring and neap tidal cycles for the three inlets (Figures 2 and 3, respectively). Chl a had higher concentrations in the

Table 1. Residual tidal prisms and net transport of suspended solids (SS), chlorophyll a (Chl a) and nutrients at the three inlets, Ancão (BAN), Faro-Olhão (BFO) and Armona (BAR), during a complete spring tide (22-24 November) and neap tide (5-7 December). Q means flow. Positive values refer to import, negative ones to export.

Spring Tide				
	INLET	BAN	BFO	BAR
Q residual	( $\text{m}^3$ )	$5.5 \times 10^5$	$1.4 \times 10^6$	$1.7 \times 10^6$
SS	(ton)	5.6	-19.2	8.4
Chl a		0.2	3	-0.1
TIN		-51	-723	-14
$\text{NO}_3^-$	(kg)	-32	15	-1
$\text{NH}_4^+$		-18	-726	-11
$\text{PO}_4^{3-}$		-3	-39	-2.3
$\text{SiO}_4^{4-}$		-74	234	66
Neap Tide				
	INLET	BAN	BFO	BAR
Q residual	( $\text{m}^3$ )	$-9.2 \times 10^4$	$3.4 \times 10^6$	$-6.1 \times 10^6$
SS	(ton)	0.9	-18.3	0.7
Chl a		-0.1	1	1
TIN		-47	62	-284
$\text{NO}_3^-$	(kg)	-30	115	-96
$\text{NH}_4^+$		-15	-51	-174
$\text{PO}_4^{3-}$		-6	33	-77
$\text{SiO}_4^{4-}$		-46	-0.7	-470

intermediate level at BFO during spring tide, and at the surface level in the Armona inlet in both tidal cycles. The range of values in the three inlets was similar, particularly the nutrient concentrations at both tidal peaks (HW and LW). These varied in antiphase relative to the tidal signal, with lower values during the flood than during the ebb period, due to the tidal dilution effect. However, this tidal signal was less evident during the neap tide (Figures 2 and 3) when the water volume exchanged during the tidal cycle is markedly lower. Comparing the three inlets, the smallest variability was found at BFO and the maximum nutrient concentrations were observed in the Ancão inlet, where the anthropogenic inputs due to land drainage (agricultural and golf courses runoff) and sewage discharges upon the western section of Ria Formosa could be more important (Loureiro et al., 2006). Data also show a general decrease of nutrients from spring (Figure 2) to neap tidal cycle (Figure 3). This decrease may be explained by phytoplankton consumption since during spring tide Chl a was relatively higher than during the neap tidal cycle. It means that during neap tides, when the tidal amplitude is reduced and the time of residence increases, factors other than tide may explain the chemical variability of the waters, such as the phytoplankton activity. Concentrations of Chl a (mean generally  $< 0.5$   $\mu\text{g/L}$ ) and suspended solids (mean  $< 10$   $\text{mg/L}$ ) were lower during the neap tidal cycle with less evident tidal variation than for nutrients (Figures 2 and 3), and highest at the Faro-Olhão inlet. These values are typical and similar to those for coastal waters close to the inlets of Ria Formosa by this time of the year (Falcão and Vale, 2003; Cardoso et al., 2005; Newton and Mudge, 2005; Barbosa, 2010).

The estimated tidal prism for both tidal cycles (Table 1) shows that during the spring tide all the three inlets acted as flood-dominated inlets, with the highest residual flow in the Armona inlet ( $1.7 \times 10^6$   $\text{m}^3$ ). The Faro-Olhão inlet was for both tidal cycles a flood dominated inlet ( $1.4$ - $3.4 \times 10^6$   $\text{m}^3$ ). Others authors studying the tidal prism at the main inlets of the Ria Formosa had also identified this inlet as the main flood-dominated (Duarte et al., 2008; Pacheco et al., 2010). During the neap tide the tidal prism in

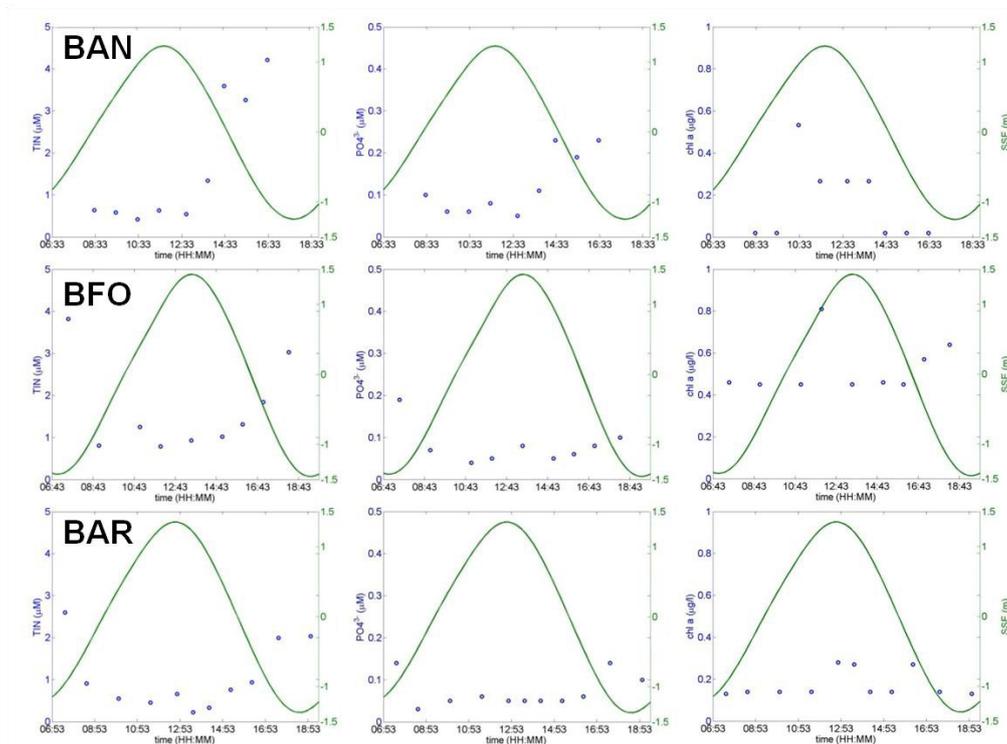


Figure 2. Variation of sea surface elevation (SSE) and mean concentrations of TIN,  $\text{PO}_4^{3-}$  and Chl a during the complete spring semidiurnal tidal cycle between 22 and 24 November 2011 at the inlets: Ancão (BAN), Faro-Olhão (BFO) and Armona (BAR).

the Armona and Ancão inlets reversed. The Armona inlet acted as the main ebb-dominated inlet ( $-6.1 \times 10^6 \text{ m}^3$ ) while the Ancão inlet had the minimum residual tidal prism ( $-9.2 \times 10^4 \text{ m}^3$ ). These estimates are of the same order of magnitude to that previously found by Pacheco et al. (2010) for these two inlets, despite showing some differences. Such differences may be associated with small variations of the tidal height and due to small differences in the ebb and flood periods since these are tropical tides, showing differences of tidal height in the two daily successive tides. However, the results confirm the interconnectivity between inlets resulting in a recirculation pattern through the main channels that connect them. The water inflowing to the Ria Formosa system through the Faro-Olhão inlet is distributed both west and eastwards, where the Armona and Ancão act mainly as ebb dominated inlets (Duarte et al., 2008).

The net transport of nutrients, SS and Chl a were also estimated and data (Table 1) show that Ria Formosa has a major role in the export of nutrients to the adjacent coastal area, particularly during spring tides, with the greatest contribution of the Faro-Olhão inlet. This inlet presented an unusual behaviour during both tidal cycles. Despite being a flood-dominated inlet during both tidal cycles, importing Chl a (1-3 kg) and  $\text{NO}_3^-$  (11-115 kg), it exported  $\text{NH}_4^+$  (~50-725 kg), and SS (~18-19 ton) to the coastal zone. During spring tide the Chl a import was higher than during neap tide, also importing silicate and nitrate while during neap tide it imported mainly nitrate and phosphate. The Armona inlet, regardless the flow direction of the water, imported SS (~1-8 ton) and exported nutrients of N (TIN: 14-284 kg) and P (2-77 kg). Particularly during neap tides the Armona inlet was the most important inlet to the coastal export of nutrients, even importing Chl a and SS. The Ancão inlet behaved similarly to the Armona inlet, from where in

both tidal cycles, nutrients were exported while SS were imported. The particulate matter imported explains the sand accretion observed in the interior region of these two inlets (flood tidal deltas). It is also important to note that in the Ancão inlet, although it contributes to the lowest water exchanges (Table 1), exhibited the maximum transport of  $\text{NO}_3^-$  during spring tide (32 kg), confirming that the westernmost region of this sector of Ria Formosa represents a source of this nutrient (Loureiro et al., 2006) to the coastal zone. Moreover in the neap tidal cycle  $\text{SiO}_4^{4-}$  was consistently exported to the ocean through the three inlets, but mainly by Armona inlet (470 kg). The silicate export has already been pointed out as a regular trend from the main inlets of Ria Formosa (Falcão and Vale, 2003), and this was also confirmed recently in the Ancão inlet (Alcântara et al., 2012).  $\text{NH}_4^+$  was also exported through the three inlets for both tidal cycles, as already reported in the Faro-Olhão inlet (Newton and Mudge, 2005).

Considering that Ria Formosa exports nutrients fertilizing the adjoining ocean through the several inlets, this will increase the productivity of the coastal zone (Falcão and Vale 2003; Newton and Mudge 2005). However, some import of material was also observed, particularly at the Faro-Olhão, a flood dominated inlet. The import of  $\text{NO}_3^-$ ,  $\text{PO}_4^{3-}$  and Chl a from the adjacent ocean has already been pointed out for the inlets of Ria Formosa (Falcão and Vale, 2003) and in this case may also be influenced by a previous upwelling event (mid October–first week of November) along the south Portuguese coast, in front of Ria Formosa, reflected by an increase of Chl a (Figure 4). During these events nutrients and Chl a may be supplied into the Ria Formosa with values around  $1 \text{ mg m}^{-3}$  (Figure 4). In fact the maximum Chl a values were recorded at the Faro-Olhão inlet in the spring tidal cycle.

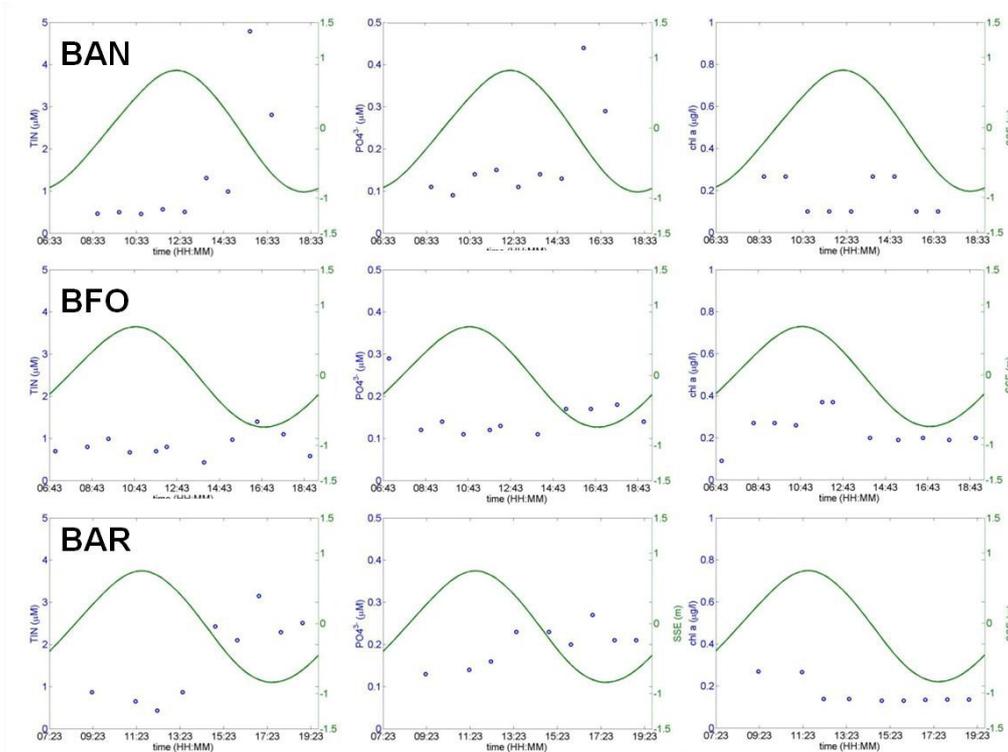


Figure 3. Variation of sea surface elevation (SSE) and mean concentrations of TIN,  $\text{PO}_4^{3-}$  and Chl a during the complete neap semidiurnal tidal cycle between 5 and 7 December 2011 at the three inlets: Ancão (BAN), Faro-Olhão (BFO) and Armonia (BAR).

Nevertheless, these data are only representative for the surveyed late autumn conditions. Values can change due to daily tidal range variability (tropical tides), tidal asymmetry and distortion, and modification in the interconnection of inlets inside the lagoon. In addition, the results confirmed that the water characteristics at the three inlets are not only affected by the tidal range. Data may change in time either due to changes in tidal dynamics or by alteration of biological and chemical processes occurring in the boundary waters, affected by atmospheric and oceanographic processes, such as coastal upwelling. To further understand the mass exchange and the dynamics of nutrients, SS and Chl a through this western sector of the Ria Formosa, from where more than 90% of the waters within this system is exchanged, it is important to evaluate those processes at a seasonal scale. To comprehend the global functioning of the inlets in Ria Formosa and potential impact upon the adjacent coastal zone, the configuration of the inlets connected with each other through a complex system of tidal channels must be considered, as it has been in the ongoing COALA Project.

### CONCLUSION

- Ria Formosa is a productive coastal lagoon and these data for late autumn conditions show that this system has a major role in mass export of nutrients to the adjacent coastal area.
- Chl a concentration in the Ria Formosa during both surveys was not particularly high and as a consequence the nutrient levels were within typical ranges for this time of the year.
- The Ancão inlet had the lowest net water discharges and independently from water exchanges (import or export),

exported nutrients and imported SS. The Faro-Olhão inlet, in both tidal cycles imported water, Chl a and  $\text{NO}_3^-$  and exported SS and  $\text{NH}_4^+$  and during spring tides is the most important one in terms of exchanges with the adjacent coastal waters. The Armonia inlet consistently imported SS and exported  $\text{NO}_3^-$ ,  $\text{NH}_4^+$  and  $\text{PO}_4^{3-}$ .

- Results of transport depend on the tidal range (tropical tides; difference of tidal height in 2 successive tides, showing different periods of ebb and flood) and also on interconnection between inlets.
- Data may also change depending on meteorological conditions, biological and chemical characteristics of the boundary water masses mixing associated with oceanographic processes (e.g. upwelling at the adjacent coastal area).
- To further understand the dynamics of nutrients, SS and Chl a and their mass exchange through Ria Formosa more surveys will be conducted at these three main inlets of the western sector, to understand their spatial evolution at a seasonal scale.

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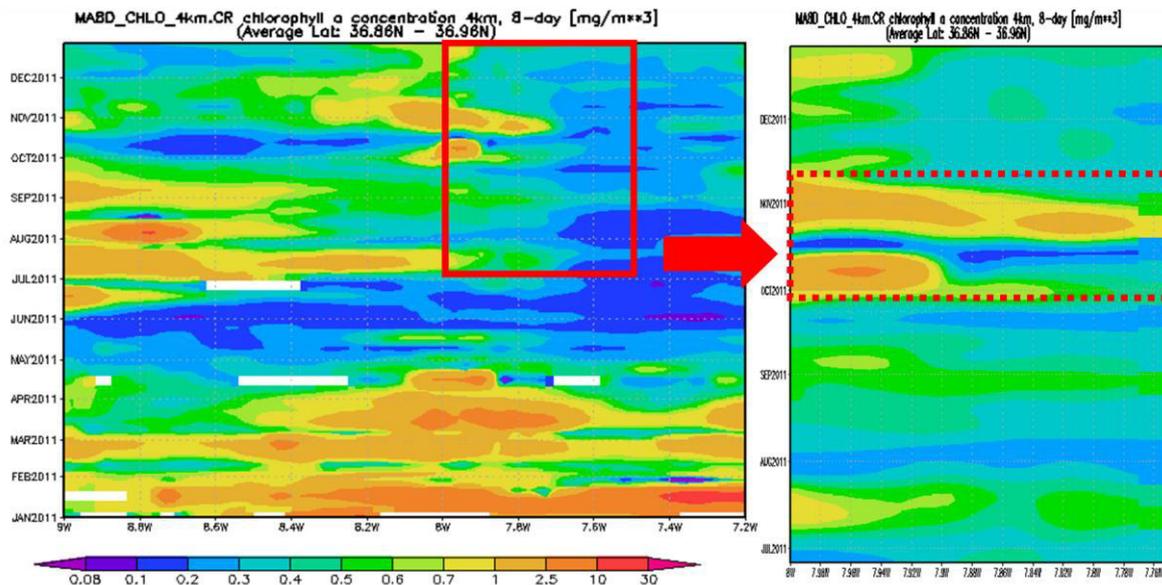


Figure 4. Hovmuller diagram of monthly averaged SeaWiFS chlorophyll a along a section (7.2°W to 9°W) off the southern coast of Portugal, from January to December 2011, generated by the NASA Giovanni website. Chlorophyll a concentrations ( $\text{mg m}^{-3}$ ) were averaged between 36.86°N and 36.96°N (top image) as well as along the section 7.75°W to 8°W, to include the area close to the 3 studied inlets in Ria Formosa, in the period from July to December 2011 (bottom image). The dashed rectangle is pointing out the highest Chl a concentration in the period middle October-beginning of November 2011.

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