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Integrating physical and biogeochemical processes and oceanic exchanges at a coastal lagoon in Southern West Europe

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A B S T R A C T

Coastal lagoons are highly productive systems and the quantification of mass fluxes, which is of paramount importance for the sustainable management of these systems, remains poorly studied. In this context, a detailed study was conducted to better understand the exchanges between the productive coastal lagoon Ria Formosa (South-West Europe) and the ocean. The exchanges of water, nutrients, chlorophyll-a and suspended solids between the main inlets (Faro-Olhão inlet - BFO; Armona inlet - BAR; and Ancão inlet - BAN) and adjacent channels (Faro - CF and Olhão - CO) and the adjacent ocean were estimated along complete semidiurnal tidal cycles, under extreme fortnightly tidal ranges and different seasonal and environmental/oceanographic conditions. The net tidal prism was highest during spring tides. Among the three inlets, BFO was the most important in terms of exchange, followed by BAR and BAN. Net transport at BFO was lowest during the Summer campaign, although it exported material that fertilised the adjacent coast. The persistent net export of suspended solids and ammonium suggests the higher biological productivity of Ria Formosa compared to that found in coastal waters. In the Winter campaign, after a period of rainfall and increased land runoff, there was a remarkable export of matter, on which, ammonium and suspended particles exported can exceed 0.3 times and almost 0.9 times, respectively, those imported from coastal water. However, the import of phosphate and nitrate can be attributed to a weak coastal upwelling event, as well to low consumption and nitrification at this period of low temperature. During the Spring and Autumn campaigns, the Ria Formosa was fertilised either by upwelling events or due to rapid consumption of nutrients by phytoplankton in this shallow system. BFO and the other two inlets of the western sector of Ria Formosa are interconnected by CF and CO. The higher nutrient transport was recorded at CF, despite the highest nutrients concentrations was recorded at CO. The data show the strong link between physical and biogeochemical processes with meteorological/oceanographic factors. The study showed that associated biological processes are superimposed on the tidal effect in this system. Data from this study could be used as a reference, particularly important for management of Ria Formosa, a productive system where bivalves production depends deeply on water quality. In addition, the nutrient concentrations and mass exchanges resulting from the different processes can be used as a reference for other lagoon systems where shellfish production is practised.

1. Introduction

Coastal environments provide a wide range of goods, services and human activities and are highly valuable to society (Newton et al., 2014). These coastal systems are highly dynamic and productive, but vulnerable to human pressure and potential impacts, including those associated with climate change (Anthony et al., 2009; Chapman, 2012). Because of their importance, it is crucial to know how current conditions and potential future changes will affect biogeochemical cycles, metabolism and ecosystem functioning. Coastal lagoons and coastal oceans are tightly coupled ecosystems and understanding their coupling is fundamental to comprehend the feedbacks and interactions between terrestrial and marine cycles, which play an important role in the biogeochemical cycling of various elements (Lobo et al., 2023). These

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systems play a key role in regulating the fluxes of water, nutrients and organisms between land, rivers and the ocean (Brito et al., 2010; Newton et al., 2014). Nevertheless, and despite the progress and increase in observational programmes on coastal processes, the quantification of mass fluxes through these interconnected systems, which are of paramount importance in controlling lagoon water quality and biological productivity, remains poorly studied. Therefore, chemical and biological observations coupled with physical and hydrodynamic processes are fundamental to estimate fluxes/transport through these interconnected environments, to understand the current situation as well as to predict future scenarios of change (natural or anthropogenic).

Water quantity and quality in a coastal lagoon is influenced by the rate at which the lagoon loses or gains water from exchange with the ocean, or from surface runoff, evaporation, precipitation and groundwater input (Allen et al., 1981). The lagoon–ocean exchanges through inlets are mainly driven by tides (Zimmerman, 1981), being responsible for the lagoon water balance (Smith, 1994). The magnitude of tidal influence and patterns of circulation/hydrodynamics are key physical properties that control the water retention time and material exchanges. The water renewal is promoted depending on the size and shape of the lagoon, the level of connectivity with the ocean, the tidal range and the freshwater flow (Phleger, 1981). However, the water quality is not only controlled by tidal cycles, but also by other driving mechanisms. In coastal lagoons, nutrients can be transported either from the ocean by upwelling or from land by superficial runoff and/or groundwater or by diffusion from sediments, which are responsible for high rates of primary production that support high rates of secondary production compared to other aquatic ecosystems (Nixon, 1982, 1995). Observations in the continuum between the inlets and the adjacent sea, and through the main channels, are therefore of key interest, fundamental to understanding their coupling and identifying their role in regulating water, nutrient and organism fluxes. The concentration of carbon, nitrogen and phosphorus compounds in water bodies located at the land-sea boundary varies as a result of their inputs and outputs, hydrodynamics, water and sediment exchange, and the interactions of biological processes (Buzzelli et al., 2013). However, the transport, retention and transformation of matter involved in biogeochemical processes in estuaries and coastal lagoons are strongly affected by the hydrological and climatic characteristics of each region (Medina-Galván et al., 2021). Budgets are a powerful tool because they allow assessment of the relative importance of external sources (and hence underlying causes), internal biogeochemical processes and water exchange (Artioli et al., 2008).

In Ria Formosa lagoon, a multi-inlet system in southern Europe (Portugal; Fig. 1), as in other similar mesotidal systems, water quality and mass exchange are mainly determined by tidal interaction with the ocean and internal circulation due to the interconnection of channels within the system (Newton and Mudge, 2005). Its high productivity is well known, especially during the Spring and Autumn seasons when phytoplankton blooms at the inlets in contact with the adjacent ocean are more frequent (Barbosa, 2010). This system is of great socio-economic importance, being the main national producer of bivalve molluscs (~90%), whose activity directly and indirectly employs about 10,000 people. The intertidal shellfish production areas (Fig. 2), although spread over large areas along the Ria Formosa, are mostly concentrated between the cities of Faro and Olhão, representing more than 80% of the total harvest from this lagoon. These areas are highly dependent on primary production and water quality, and are located close to salt marshes and include both inner zones with restricted circulation and outer zones close to the main inlets (Fig. 2). Therefore, the global biological productivity of Ria Formosa, which is dependent on water quality, is also controlled by the renewal of water through the main inlets and channels and by the patterns of water circulation.

There is a considerable amount of multidisciplinary research within the Ria Formosa, including its inlets and channels. From a hydrodynamic point of view, some studies can be highlighted, after the 2000s, dedicated to the circulation between the main inlets and the adjacent channels (Faro and Olhão) (Salles et al., 2005; Pacheco et al., 2010). More recently, hydrodynamic modelling approaches have also studied circulation patterns and the main channels (Fabião et al., 2016). At the same time, Jacob and Cravo (2019) reported the contribution of each of the three inlets of the western sector of Ria Formosa and the circulation patterns between them. However, understanding and quantification of the mass balance of nutrients, chlorophyll-a and suspended solids that control biological productivity are still limited, with the exception of those focused on lagoon-sea water exchanges, namely in the western sector, which accounts for about 90% of water exchanges with the adjacent ocean (Alcântara et al., 2012; Cravo et al., 2014, 2019; Malta et al., 2017; Rosa et al., 2019). Nevertheless, nutrients, chlorophyll-a and suspended solids exchanges through the three inlets of this sector and on its main channels are still undocumented.

In this context, the main objectives of the present study are: i) to understand the role of the mass exchange of nutrients, chlorophyll-a (as a proxy for phytoplankton growth) and suspended solids through the interconnectivity of the western sector of Ria Formosa (Faro-Olhão, Armona and Ancão inlets) with the adjacent ocean during the productive seasons (Spring and Autumn; Winder and Cloern, 2010; Martinez et al., 2011) and extreme tidal range (neap tides *versus* spring tides); ii) the seasonality of these exchanges at the main inlet of this sector, during spring tides, when the exchanges are intensified; iii) the interconnectivity between the main Faro-Olhão inlet and the adjacent channels - Faro and Olhão - during Autumn conditions, in two

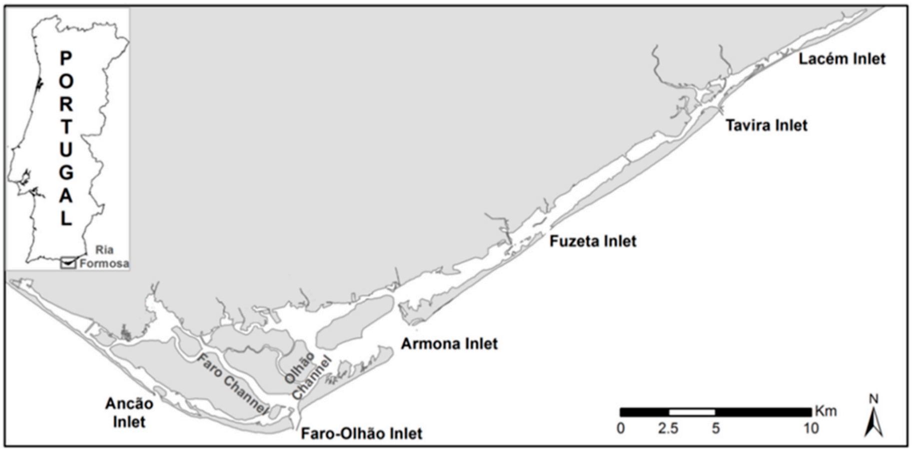

Fig. 1. Location of Ria Formosa coastal lagoon system with indication of the tidal inlets and the two main channels of Faro and Olhão.

Fig. 2. Orange polygons indicate the location of shellfish beds in the western sector of Ria Formosa. Sections sampled at BFO, CF (Faro Channel) and CO (Olhão Channel) are indicated with a white line and the Pressure Transducers deployment location with a yellow star symbol. Image retrieved from: https://webgis.dgrm.mm.gov.pt/portal/apps/webappviewer/index.html?id=8998c9b4e9dd436f94a4785c2da89478.(For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

consecutive years, under spring and neap tide conditions. This will allow the understanding of the processes involved and to establish the link between the physical and biogeochemical processes in this sector of Ria Formosa. To this end, *in-situ* and remote sensing observations have been carried out, together with analyses of the main physical, chemical and biological processes that shape coastal ocean-lagoon ecosystems. The knowledge of the physical, chemical and biological processes of this lagoon system, associated with the knowledge of its hydrodynamics, can contribute to better management of bivalve mollusc's production with economic relevance to the region.

2. Material and methods

2.1. Study area

Ria Formosa is a shallow coastal lagoon of about 100 km^2, 55 km long, with a maximum width of 6 km and an average depth of less than 2 m, located on the south coast of Portugal (Fig. 1). It has a mean tidal range of about 2 m, is dominated by the semi-diurnal component of the tide, and has six permanent connections to the ocean, responsible for a high renewal rate. The tide is the dominant driving force for the circulation within the lagoon. Approximately 50–75% of the water mass is exchanged every semi-diurnal tidal cycle (Newton and Mudge, 2003; Brito et al., 2010; Meyers et al., 2010) and there is no evidence of persistent haline or thermal stratification due to reduced freshwater inputs, especially in the outer areas of Ria Formosa (Alcântara et al., 2012; Cravo et al., 2014; Rosa et al., 2019, 2022). Consequently, the water column is well mixed vertically. The water residence time is low, especially in the inlets and main channels, and increases towards the inner parts of this system (Fabião et al., 2016; Cravo et al., 2020).

The western sector of Ria Formosa consists of Ancão, Faro-Olhão and Armona inlets (Fig. 1) and represents approximately 90% of the total tidal prism of the entire lagoon (Pacheco et al., 2010). The Ancão inlet is located on the western flank of this sector and the Faro-Olhão and Armona inlets are located on the eastern flank of the same sector, which includes several channels and creeks. The two main channels are the Faro Channel (CF), which connects the Faro-Olhão inlet to the city of Faro, and the Olhão Channel (CO), which connects the same inlet to the city of Olhão. The Faro-Olhão inlet is the most important, being responsible for about 60–70% of the tidal prism (Pacheco et al., 2010; Jacob and Cravo, 2019).

Faro-Olhão inlet was artificially opened and stabilised with jetties between 1929 and 1955. As a result of these processes, a large tidal prism from the Armona Inlet was captured by this inlet. Armona Inlet is the only naturally stable inlet in the system. It was the dominant natural inlet in the system, but the development 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). In addition, Armona inlet has been narrowing over time (Pacheco et al., 2010) and there is no evidence that it has stopped (Jacob and Cravo, 2019). Ancão inlet is a small inlet with a cyclic eastward migration. The relocation it has undergone was necessary to improve water exchange and reduce hydraulic losses.

A strong residual circulation from Faro-Olhão inlet is directed towards Ancão and Armona inlets during both spring and neap tides (Pacheco et al., 2010). An internal circulation pattern operates in the main tidal channels of Ria Formosa (Faro and Olhão channels): Olhão Channel acts mainly as a flood-dominated channel, while Faro Channel is responsible for the residual ebb towards the main inlet (Pacheco et al., 2010). During neap tides, the connectivity between the inlets is reduced as they cover a large area and the adjacent channels are too shallow to provide a significant hydraulic connection.

From a hydrodynamic point of view, Faro Channel is considered to be the largest in the Ria Formosa and the most hydraulically efficient. The channel has a general NW-SE orientation and is 9 km long. The typical depth of the channel is between 6 m and 12 m below the Mean Sea Level (Silva et al., 2002). Currents near the inlet can reach maximum values of 2.22 m/s during ebb conditions and 1.59 m/s during flood conditions (IH, 2000; Silva et al., 2002). Olhão channel is shallower, wider, with lower current velocity (Ventura Soares et al., 2001).

It is also important to note that the density of shellfish beds for clam production is much higher near the Olhão Channel than the Faro Channel, as can be seen in the areas outlined by the orange polygons in Fig. 2. It can also be seen in this figure that the area further north of the Faro-Olhão inlet consists of salt marshes with shallow and narrow secondary channels, while the area on the side of CO is much wider than that on CF.

2.2. Field surveys

The location of the three sampling sites at the inlets (BFO, BAR and BAN) in the western sector of Ria Formosa, and the channels adjacent to the main inlet BFO (Faro Channel and Olhão Channel) is shown in Fig. 2. Sixteen oceanographic campaigns were carried between 2011 and 2013, over complete semi-diurnal tidal cycles (*ca.* 12.5 h) as shown in Table 1.

A first set of six campaigns was conducted in the Autumn (November/December) of 2011, consisting of three in spring tide and three in neap tide, in three consecutive days at BAN, BAR and BFO. The same approach was used in a second set of six campaigns carried out in the following Spring season (March 2012), except BFO in neap tide that was sampled 1.5 months later (mid-May) due to a technical problem and logistic constraints. The Winter campaign at BFO was carried out after a period of rain typical of winter conditions (sum of precipitation over the 10 previous days = 44 mm, as reported in Rosa et al., 2019), in March 2013 that also matched a period of upwelling. The Summer campaign was conducted at BFO in July 2013, under typical warm and dry conditions. The adjacent channels, CF and CO, were sampled only in Autumn (2011); 2012 campaigns, at both spring and neap tides.

Flow velocity was measured hourly along the cross-section of the inlets and channels, using a Sontek/YSI 1.5-MHz Current Surveyor Acoustic Doppler Profiler (ADP) with bottom tracking, side mounted on a boat. Bottom-tracking allows the ADP to measure both its velocity (speed and direction) over the Earth and the water depth beneath the system. These data were used to remove vessel motion from measured water velocity to determine the “true” water speed and direction (Sontek, 2005). The cell size and blanking distance were set to 0.4 m, the ADP transducer draft to 0.25 m and the number of cells to an appropriate number that accounted for the maximum depth of each profile. The ADP was operated in continuous mode with a 5 s average interval. The software Current Surveyor v4.6 was used to record hydrodynamic data, to measure the cross-section shape and dimensions and to analyse the hourly transect surveys. The signal-to-noise ratio (SNR) was set to 3 dB to remove invalid data below the ambient noise level.

Table 1
Characteristics of the oceanographic campaigns carried out at the three inlets (Faro-Olhão, Armona and Ancão inlets) and at the two channels (Faro Channel-CF and Olhão Channel-CO) of the western sector of the lagoon, including date, tidal phase, tidal range and cross-sectional area.

Inlet	Date	Tidal Phase	Tidal Range (m)	Cross-sectional area (m^2)
Ancão	22-11-2011	Spring Tide	2.53	365
Armona	23-11-2011		2.79	3082
Faro-Olhão	24-11-2011		2.95	5988
CF	24-11-2011		2.95	6124
CO	24-11-2011		2.95	4168
Faro-Olhão	05-12-2011	Neap Tide	1.43	4808
CF	05-12-2011		1.43	4467
CO	05-12-2011		1.43	3061
Armona	06-12-2011		1.6	2661
Ancão	07-12-2011		1.76	315
Armona	21-03-2012	Spring Tide	2.51	3309
Faro-Olhão	22-03-2012		2.61	6147
Ancão	23-03-2012		2.63	481
Ancão	28-03-2012	Neap Tide	1.66	427
Armona	29-03-2012		1.34	3126
Faro-Olhão	14-05-2012		1.27	5697
Faro-Olhão	09-10-2012	Neap Tide	1.1	5548
CF	09-10-2012		1.1	3431
CO	09-10-2012		1.1	6550
Faro-Olhão	16-10-2012	Spring Tide	3.32	6493
CF	16-10-2012		3.32	4300
CO	16-10-2012		3.32	6844
Faro-Olhão	13-3-2013	Spring Tide	2.92	6393
Faro-Olhão	10-7-2013	Spring Tide	2.41	5697

Water samples for the analysis of nutrients, suspended solids (SS) and chlorophyll-a (Chl-a) were also collected hourly at a central point of the section (Fig. 2), at three levels of depth along the water column (1 m below surface, Secchi disk extinction depth and 1 m above the bottom, max. 13 m), using a Niskin bottle (5 L). Concurrently, at the Faro and Olhão channels (Fig. 2) a similar sampling strategy was carried out, but as the depth of the water column was <10 m, water sampling measurements were conducted only at surface and bottom levels. A central point was selected considering that 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 middle and extremes). Additionally, measurements of temperature, salinity, pH and dissolved oxygen were conducted *in-situ* using a YSI 6820 multi-parametric probe, at the same levels from where the water samples were taken.

2.3. *Discharges, tidal prisms and mass transport*

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 along the flood and ebb periods provided respectively the flood and ebb tidal prisms. The residual tidal prism or net transport of water was obtained as the difference between the flood and ebb tidal prisms or, equivalently, through the numerical integration of the discharge over the complete semi-diurnal tidal cycle.

The transport of nutrients, suspended solids and Chl-a, in $kg.s^{-1}$, was calculated hourly over the entire tidal cycle, multiplying the discharge by the cross-sectional average concentration. Finally, the tidal prisms (m^3) and the net transport of nutrients (kg), suspended solids (tonnes) and Chl-a (kg) were obtained by integrating the hourly transport values in the time domain over the entire tidal cycle.

2.4. *Laboratorial analysis*

For nutrients analysis (0.25 L), the samples were filtered through decontaminated and weighed membrane filters (0.45 μm, for further Suspended Solids determination) and frozen at −20 °C. For Chl-a determination, 1 L water samples were filtered using GF/F glass fibre filters, which were frozen at −20 °C until analysis. Nutrients and Chl-a were spectrophotometrically determined by the methods described in Grasshoff et al. (1999) and Lorenzen (1967), respectively, while SS were determined through gravimetric methods described in APHA (2002). Detection limits for nutrients determination were 0.1 μM for NH_4^+, 0.05 μM for $NO_2^- + NO_3^-$, 0.02 μM for PO_4^{3-} and 0.05 μM for $Si(OH)_4$ and 0.2 μg/L for Chl-a. 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 ±1% for $Si(OH)_4$ and PO_4^{3-} and ±2% for NO_3^-.

2.5. Environmental and oceanographic settings

Eight-day composites of satellite-derived data for Sea Surface Temperature (SST) and Chla concentrations were obtained from the Copernicus Marine Service data catalog,[2] including for the periods before, during and after the field surveys. The analysis of SST was based on a Level 3 data product (SST_ATL_PHY_L3S_MY_010_038) at ca. 5 km spatial resolution. The analysis of Chla concentrations was based on a Level 3 data product (OCEANCOLOUR_ATL_BGC_L3_MY_009_113) at 1 km spatial resolution. These datasets, together with the wind dataset, were fundamental to confirm the oceanographic and meteorological processes influencing the results from the observations.

Time series of sea level and water temperature data collected with pressure sensors placed in two different locations in the Ria Formosa (BFO and port of Faro; Fig. 2) were analysed, together with simultaneous series of wind velocity and precipitation from the meteorological station at Faro airport. To remove high-frequency signals from the analysed time series, a low-pass Butterworth filter was used: in the sea level and water temperature time series, a cut-off frequency fc=(1/48) hours-1 was used to remove the semi-diurnal and diurnal tide components, the most important; and in the wind series, a cut-off frequency fc=(1/30) hours-1 was used for graphical representation and analysis of large-scale variability in the wind field.

2.6. Statistical analysis

To test whether there were significant differences along the water column, one-way ANOVA test with 95% confidence interval followed by post-hoc Tukey was used for variables with normal distribution, while Kruskal-Wallis for variables with non-normal distribution. The same approach was applied to test the significant seasonal, spatial and tidal differences between variables at the three inlets, between different seasons at BFO, between spring tides and neap tides and differences between BFO and the adjacent channels (CO and CF) in Autumn (2011); 2012 campaigns. Kruskal-Wallis (with 95% confidence) was used because at least one of the campaigns had a non-normal distribution.

3. Results

Before presenting the mass exchanges through the main inlets and channels of the western sector of Ria Formosa, it is important to contextualise the characterisation of the water quality and summarise the main features observed. The range and median values of temperature, salinity, dissolved oxygen, nutrients (ammonium, nitrate, phosphate, silicate), Chl-a and suspended solids recorded at the three inlets of the western sector of Ria Formosa and adjacent channels of the BFO (CF and CO), along the water column and over the entire tidal cycle during the 16 campaigns, are presented in Tables SM 1 to SM 3 of the Supplementary Material (SM). Data from the Autumn and Spring campaigns (Table SM 1 in SM) show that temperature, nitrate and silicate at the three inlets of the western sector of the Ria Formosa were significantly lower ($p < 0.05$) during the Spring season, while salinity, percentage of saturation of dissolved oxygen, phosphate and Chl-a were significantly higher ($p < 0.05$) during this season. Ammonium and suspended solids concentrations showed no seasonal differences ($p > 0.05$) between Autumn and Spring campaigns. Spatially, concentrations were relatively similar between the inlets, regardless of the different area of each of the three inlets (Table 1). Globally, there were no significant differences ($p > 0.05$) between the three inlets for percentage of saturation of dissolved oxygen, nitrate and Chl-a (Table SM 1 in SM). However, some significant differences ($p < 0.05$) were found between the inlets. In particular. salinity, phosphate, silicate and suspended solids were higher at BAN than at any of the other inlets, ammonium was higher at BAR than at any of the other inlets, while BFO recorded higher values for water temperature than at any of the other inlets. Among the tidal conditions, the highest range of variability was found during spring tides due to the higher range of tidal heights, with nitrate and silicate being significantly higher ($p < 0.05$) during spring tides than during neap tides. However, temperature and phosphate were significantly higher ($p < 0.05$) during neap tides than during spring tides. There were no significant differences ($p > 0.05$) between spring and neap tides for salinity, percentage of saturation of dissolved oxygen, ammonium, Chl-a and suspended solids.

At the main inlet under spring tidal conditions, the seasonal variability (Table SM 2 in SM) showed that, as expected, temperature was significantly lower during the Winter campaign than during the Summer campaign ($p < 0.05$). The same trend was observed for salinity. Dissolved oxygen was significantly the highest during the Spring campaign ($p < 0.05$) and lowest during in Winter campaign. Concerning Chl-a concentrations, values were the lowest during the Winter campaign ($p < 0.05$), while the highest concentrations were found during the Spring campaign. Nitrate, phosphate and suspended solids were significantly higher ($p < 0.05$) during the Winter campaign, while ammonium and silicate were significantly higher ($p < 0.05$) during the Autumn campaign), and the minimum median concentrations of nitrate and silicate were recorded during the Summer and Spring campaigns, respectively.

In addition, the range of the same parameters studied simultaneously at the main inlet and adjacent channels under Autumn conditions during the spring and neap tides of the consecutive years 2011 and 2012 (Table SM 3 in SM) was similar. There were no significant differences ($p > 0.05$), except for ammonium, phosphate and Chl-a, which were higher ($p < 0.05$) at CO than at BFO (showing the lowest variability along the tidal cycles), and silicate, which was higher ($p < 0.05$) at CF than at BFO. Globally, data for 2011 were similar ($p > 0.05$) or significantly lower than those for 2012 ($p < 0.05$), except for suspended solids concentrations. There was no consistent trend in the variability of the data with respect to tidal conditions. There were no significant differences ($p > 0.05$) for salinity, ammonium and Chl-a. Temperature and percentage of saturation of dissolved oxygen were significantly higher ($p > 0.05$) during neap tides than during spring tides, while the concentrations of nutrients and suspended solids were significantly higher ($p < 0.05$) during spring tides than during neap tides.

To understand the magnitude of exchanges through the main inlets of the western sector and interconnection with the adjacent channels of Ria Formosa and the impact of mass exchanges with the adjacent ocean on phytoplankton growth, it is important to frame the environmental setting. This includes meteorological conditions and oceanographic processes, to retrieve information on wind direction and intensity, precipitation, and 8-days composite satellite images of SST and Chl-a, before or encompassing the sampling dates, as shown in Figures SM 1 to SM 6 in the SM. For the Autumn and Spring campaigns, the 8-day composite of SST and Chl-a satellite images prior to the sampling dates (Figures SM 1 and SM 2 in the SM) along with the wind speed and direction stick plots and SST and sea level time series graphs (Figure SM 6, top and middle panel, in the SM) denote that no upwelling events were recorded for both seasons. This is supported by the following reasons: no signal of temperature decrease was observed, wind was not westerly, the favourable direction to this process on the south coast of Portugal, and no obvious variations in Chl-a were observed. However, during the Spring campaigns, there was an increase in Chl-a concentration (≥ 3 mg m^{-3}) along the coast, stronger at the end of March and milder in mid-May, corresponding to the maximum concentration comparatively with the other campaigns (Fig. SM 2). In May 2012, inclusively, under neap tide at BFO, there was an increase of sea level accompanied by a slight increase in water temperature at the place where the PT was deployed (Fig. SM 6, middle panel in SM).

During the Winter campaign (Fig. SM 4 in SM), a weak signal of upwelling was observed, under the favourable westerly winds, with a slight decrease of the sea level and water temperature at the place where

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[2] https://marine.copernicus.eu/.

the PT was deployed (Fig. SM 6, bottom panel, in SM), together with a decrease in water temperature (3–4 °C) in front of Ria Formosa (Fig. SM 6, bottom panel, in SM), although that was not evident during the week of the campaign inside Ria Formosa (Fig. SM 6, bottom panel, in SM). However, after two weeks of the Winter campaign, the westerly favourable wind that persisted relaxed (Fig. SM 4 in SM) and high Chl-a concentrations were recorded along the south coast of Portugal, with 3–5 mg m^{-3} off Ria Formosa.

During the Summer campaign (Fig. SM 5 in SM), the presence of a warm coastal inner countercurrent (water temperature >21 °C) with low Chl-a concentrations ($\leq$1 mg m^{-3}) on the inner shelf recirculating from the Gulf of Cadiz was clear along the south coast of Portugal.

The results obtained at the three levels along the water column showed that there was no stratification ($p > 0.05$) for any of the measured parameters. The mean values integrating the water column, together with the mean water discharge were used to calculate the mass transport along the complete semi-diurnal tidal cycles and to make comparisons between sites and tidal conditions. In order to find out the influence of the exchange through the inlets, it is important to quantify the discharge, which depends on the sampled section (length and depth; Table 1) and velocity, rather than quantifying only the concentrations of the compounds, considering that even finding similar concentrations between inlets, as it is the case of the present study, the mass transport can be strikingly different due to different sectional areas, and consequently, due to different discharges. As shown in Table 1, the area of each sampled section at the three inlets of the western sector of the Ria Formosa is very different, with the smallest area at BAN, followed by BAR and the largest at BFO. The contribution of each inlet in terms of volume of water exchanged, together with nutrients, Chl-a and suspended solids, independent of season and tidal conditions, is shown in Table 2. From the three inlets, BFO is the most important, followed by BAR, while the lowest exchanges are associated with BAN.

The data obtained in this study to understand the processes affecting the biogeochemistry and mass exchanges through the coastal lagoon of Ria Formosa and to evaluate their impact on the phytoplankton are important to answer specific questions such as:

- What is the role of the mass exchange of nutrients, chlorophyll-a and suspended solids through the three main inlets of the western sector with the adjacent ocean under extreme fortnightly tidal conditions: neap *vs.* spring at the three inlets, during the most productive seasons (Autumn and Spring)?
- What is the effect of seasonal variability, at the main inlet, on phytoplankton growth, under spring tidal conditions?
- What is the connectivity between the main inlet and the adjacent channels and the role of each one in terms of mass exchange, particularly in autumn conditions (2011–2012)?

These questions are addressed in the following subsections.

3.1. Mass exchange of nutrients, chlorophyll-a and suspended solids through the three main inlets of the western sector with the adjacent ocean under extreme tidal conditions: neap tide vs. spring tide, during the most productive seasons (Autumn and Spring)

The estimated exchanges for water (volume), and Chl-a, suspended solids and nutrients (ammonium, nitrate, phosphate and silicate) transported during both spring and neap tides throughout the more productive seasons of Autumn (2011); Spring 2012 are shown in Fig. 3 and Table 3.

This figure shows that water exchanges through BAN were the lowest, followed by BAR and then BFO, and that these were intensified during spring tidal conditions. Between the Autumn and Spring seasonal campaigns, mass exchanges were globally intensified during the last season, as reflected in Table 3, for these 12 campaigns conducted during both spring and neap tides.

In terms of nutrients, Chl-a and suspended solids exchanges, net transport shows that the values were one order of magnitude lower than the flood and ebb transport and were higher during spring tides than during neap tides, maximised at BFO (Table 3). During the Spring season campaign, spring tide, at BFO there were net exchange of important mass amounts: net import of Chl-a (*ca.* 24 kg), silicate (170 kg) and nitrate (*ca.* 570 kg); and net export of ammonium (555 kg), phosphate (ca. 125 kg) and suspended solids (155 tonnes). Satellite images of Chl-a also support that phytoplankton off Ria Formosa in March 2012 was higher than in November 2011 (Figs. SM 1 and SM 2 in SM).

3.2. Exchanges through BFO under spring tidal conditions: a seasonal approach

To understand the seasonal influence on the mass exchanges through the main inlet of Ria Formosa, at BFO, during spring tidal conditions, when discharge and water renewal are the highest, mass transport was estimated in four different seasons. However, an annual seasonal sequence was not followed (Autumn: November 2011; Winter: March 2013; Spring: March 2012; Summer: July 2013).

The seasonal mass exchanges of Chl-a, suspended solids and nutrients (ammonium, nitrate, phosphate and silicate) through BFO are shown in Fig. 4. This figure shows that the largest exchanges, except Chl-a, occurred particularly during the Winter campaign, when the precipitation effect was maximum and upwelling also occurred before the campaign, despite being weak (Fig. SM 5 in SM), followed by the Autumn and Spring campaigns, while the lowest occurred during the Summer campaign. The highest Chl-a exchange was found during the Spring campaign, corresponding to a maximum import, during flood through BFO, of about 69 kg. Satellite images of Chl-a (Fig. SM 2 in SM) also confirmed that the highest Chl-a was found at the end of March 2012, suggesting the development of a typical Spring bloom until May (Fig. SM 2 in SM). Suspended solids and ammonium exchanges were maximum during the Autumn campaign, with an export during ebb from the BFO to the adjacent ocean of about 584 tonnes and 1470 kg, respectively. Nitrate, phosphate and silicate, on the other hand, had a maximum import, during flood from the ocean into Ria Formosa, during the Winter campaign, of 5950 kg, 715 kg and 4790 kg, respectively.

The net tidal prism and mass exchanges between BFO and the adjacent ocean, expressed in terms of net import and export, under these four different seasonal campaigns on spring tidal conditions are shown in Table 4. These data show that for the four seasonal campaigns, at BFO, in terms of the net tidal prism, BFO behaved dominantly as a flood inlet, globally importing water, except for the Winter campaign. During this campaign, there was a net export of water accompanied by a net export of suspended solids, ammonium, silicate and Chl-a. However, particularly nitrate and, marginally, phosphate were imported from the coast. For these four seasonal campaigns at BFO, regardless of the direction of net water transport, there was a consistent net export of ammonium and suspended solids (and phosphate, except for the Winter campaign) to the adjacent ocean. It was also estimated that during the Summer campaign, regardless of the net import of water, all the other studied compounds were exported. Particularly, phosphate was more exported during the Winter campaign (Fig. 4), while its maximum net export was found during the Spring campaign (127 kg; Table 4). During the Autumn and

Table 2
Global contribution of each of the three inlets (in percentage) of the western sector (BAN - Ancão, BAR - Armona, BFO – Faro-Olhão) in terms of water volume as well as nutrients, chlorophyll-a (Chl-a) and suspended solids (SS), regardless the season and the tidal condition, exchanged between them and the adjacent ocean.

Inlet	Water (%)	Nutrients (%)	Chl-a (%)	SS (%)
BAN	3–4	1–25	2–5	2–14
BAR	29–30	5–84	11–30	18–48
BFO	67–68	6–86	40–87	47–80

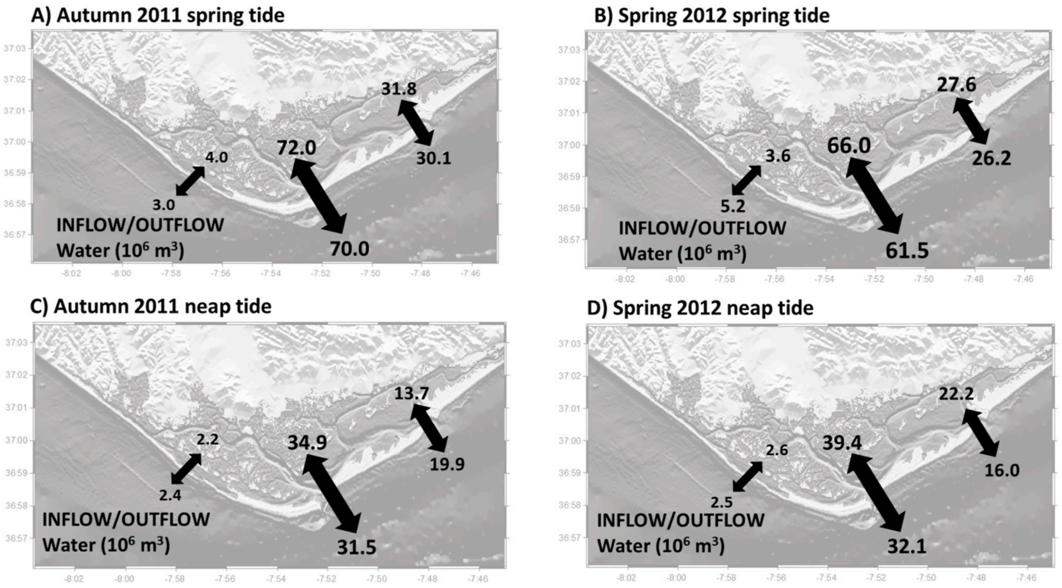

Fig. 3. Water discharge (in 10^6 m^3) between the three main inlets of the western sector of Ria Formosa (Ancão, Faro-Olhão and Armona; see Fig. 1 for location) and the adjacent ocean during ebbing and flooding phases along complete spring and neap tidal cycles in Autumn (2011); Spring 2012. The landward direction of the arrow indicated an import of matter into Ria Formosa system, while the seaward direction of the arrow indicated an export of matter from Ria Formosa to the ocean.

Table 3
– Flood, Ebb and residual transport (in bold) of chlorophyll-a, silicate, phosphate, nitrate and ammonium (in kg) and suspended solids (in tons) through the three main inlets of the western sector of Ria Formosa: BAN (Ancão Inlet); BFO (Faro-Olhão Inlet) and BAR (Armona Inlet) under spring tides (ST) and neap tides (NT) during Autumn 2011 (Aut11) and Spring 2012 (Spr12).

Period	Inlet	Tidal phase	chl-a (kg)	Silicate - Si (kg)	phosphate - P (kg)	nitrate – N (kg)	ammonium- N (kg)	Suspended solids (t)
Aut 11 (ST)	BAN	flood	0.9	196	9	17	5	26.5
		ebb	−0.5	−276	−12	−54	−29	−19.1
		residual	**0.5**	**−80**	**−3**	**−38**	**−23**	**7.5**
	BFO	flood	40.8	4100	127	356	718	428.0
		ebb	−32.3	−3720	−153	−349	−1470	−584.0
		residual	**8.6**	**376**	**−26**	**6**	**−756**	**−156.0**
	BAR	flood	5.1	1340	58	149	186	182.0
		ebb	−5.6	−1300	−61	−145	−201	−129.0
		residual	**−0.5**	**33**	**−3**	**4**	**−16**	**52.4**
Aut 11 (NT)	BAN	flood	0.3	47	9	11	4	9.9
		ebb	−0.5	−109	−16	−46	−24	−10.6
		residual	**−0.1**	**−62**	**−8**	**−35**	**−20**	**−0.7**
	BFO	flood	8.1	926	166	243	141	113.0
		ebb	−7.1	−941	−132	−119	−207	−131.0
		residual	**0.9**	**−15**	**34**	**123**	**−66**	**−17.9**
	BAR	flood	3.6	464	59	124	72	67.7
		ebb	−2.7	−996	−135	−219	−251	−66.4
		residual	**1.0**	**−533**	**−77**	**−95**	**−179**	**1.4**
Spr 12 (ST)	BAN	flood	21.4	473	123	84	247	55.9
		ebb	−3.0	−294	−33	−21	−24	−29.7
		residual	**−0.8**	**−118**	**−8**	**−2**	**6**	**−1.5**
	BFO	flood	1.5	74	14	2	6	15.0
		ebb	−45.0	−1730	−401	−872	−574	−250.0
		residual	**23.6**	**170**	**−127**	**572**	**−555**	**−135.0**
	BAR	flood	2.2	177	25	19	29	28.2
		ebb	−15.8	−238	−100	−45	−254	−67.7
		residual	**5.5**	**236**	**23**	**38**	**−7**	**−11.7**
Spr 12 (NT)	BAN	flood	68.6	1900	274	1440	19	114.0
		ebb	−1.7	−86	−13	−6	−20	−16.4
		residual	**−0.2**	**−12**	**1**	**−4**	**−15**	**−1.4**
	BFO	flood	32.2	2010	256	48	325	136.0
		ebb	−19.5	−1710	−130	−122	−340	−108.0
		residual	**12.8**	**294**	**126**	**−74**	**−16**	**28.3**
	BAR	flood	34.4	339	116	50	77	140.0
		ebb	−27.3	−219	−85	−7	−123	−106.0
		residual	**7.0**	**121**	**30**	**43**	**−46**	**33.8**

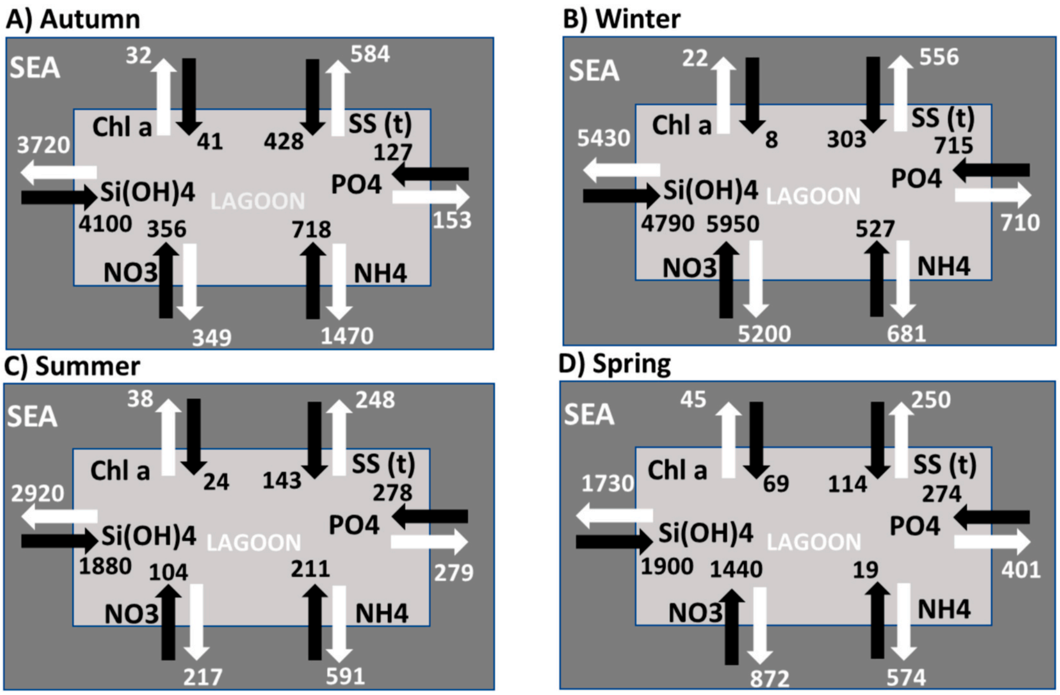

Fig. 4. Seasonal transport of import and export of chlorophyll-a (in kg) suspended solids (in tonnes), ammonium, nitrate, phosphate and silicate (in kg) exchanged between the lagoon at BFO (Faro-Olhão) inlet (see Fig. 1 for location) and the adjacent ocean under spring tidal conditions, during ebbing and flooding phases along a complete tidal cycle in a clockwise direction: Autumn 2011 (A), Winter 2013 (B), Summer (C) 2013, and Spring 2012 (D). The direction of the grey arrows indicated an import of matter into Ria Formosa lagoon, while the white arrows in opposite direction, an export of matter from Ria Formosa seaward, from the lagoon to the ocean.

Table 4
Seasonal net exchanges (import/export) trend through BFO of water, chlorophyll-a (Chl a), suspended solids (SS in tonnes), phosphate (PO4, in kg), silicate (Si(OH)4 in kg), ammonium (NH4 in kg) and nitrate (NO3 in kg) during Autumn, Winter, Spring and Summer campaigns.

SEASON	Water prism (10^6 m^3)	Net IMPORT	Net EXPORT
Autumn	Import (1.4)	Chl a, Si(OH) 4, NO3 (8.6, 376, 6.2)	SS, NH4, PO4 (156, 765, 25.5)
Winter (land runnoff + upwelling)	Export (-0.2	NO3, PO4 (750, 5)	SS, NH4, Si(OH)4, Chl a (253, 154, 643, 13.8)
Spring (spring bloom)	Import (4.5)	Chl a, Si(OH) 4, NO3 (23.6, 170, 572)	SS, NH4, PO4 (135, 555, 127)
Summer	Import (0.8)		SS, NH4, Si(OH)4, Chl a, PO4, NO3 (110, 380, 1040, 14.3, 6.8, 113)

Spring campaigns, the trend of the direction of net mass exchanges was the same: import of Chl-a, nitrate and silicate and export of suspended solids, ammonium and phosphate. Silicate had the highest exchanges during the Winter campaign, particularly on the ebb phase (Fig. 4), but its net maximum transport was during the Summer campaign (1040 kg; Table 4). Chl-a was net imported from the coast during the Spring and Autumn campaigns (24 and 9 kg, respectively), and exported during the Summer and Winter campaigns (ca. 14 kg, for both seasons; Table 4), while nitrate was net imported during all the campaigns (maximum during the Winter campaign, 750 kg; Table 4), except during the Summer campaign (net export of 113 kg; Table 4).

Upwelling showed to be an important process for nutrient supply of the Ria Formosa. Indeed, comparing two campaigns carried out at BFO (and adjacent channels) in Autumn of 2012 (detailed in the next subsection), one during neap tide and the other during spring tide (Fig. 5), under stronger upwelling influence (Figs. SM 3 and SM 6, bottom panel, in SM), it was observed that, although the BFO behaved as a net ebbing inlet in terms of water exchange, exporting water, under the influence of upwelling there was an important net import of nitrate, silicate, phosphate and Chl-a. The net transport for these two Autumn 2012 campaigns, shown in Table 5, illustrates that exchanges were greater during the spring tidal conditions, under influence of a stronger conditions of upwelling than under the previous neap tide.

3.3. *Interconnection between the main inlet and adjoining channels in autumn conditions*

Considering that in Ria Formosa there is a strong interconnectivity between the main inlets and the main and secondary channels, through a highly branched system of a complex network of natural and partially dredged subtidal channels (Barbosa, 2010), the intention was to understand the contribution of the adjacent channels connected to the main inlet, i.e. the Faro Channel (CF), also connected to the Ancão inlet, and the Olhão Channel (CO), also connected to the Armona inlet (Fig. 2). To this end, the results of four campaigns were compared under Autumn conditions (yet representative of a season of high phytoplankton activity), two in Autumn (2011) under spring and neap tides (24 November and 5 December, respectively, described in the first subsection of the results, with no influence of upwelling), and repeated in Autumn (2012) (9 and 16 October), in neap and spring tides, respectively, as described in the previous subsection, the last one under influence of upwelling.

The volume of water exchanged, together with the mass exchanges of suspended solids, Chl-a, ammonium, nitrate, phosphate and silicate of each of the main adjacent channels (CO and CF) and BFO, along complete semi-diurnal cycles under spring and neap tides, in ebb and flood, and the net exchanges during these four campaigns in Autumn (2011); 2012, are shown in Fig. 6.

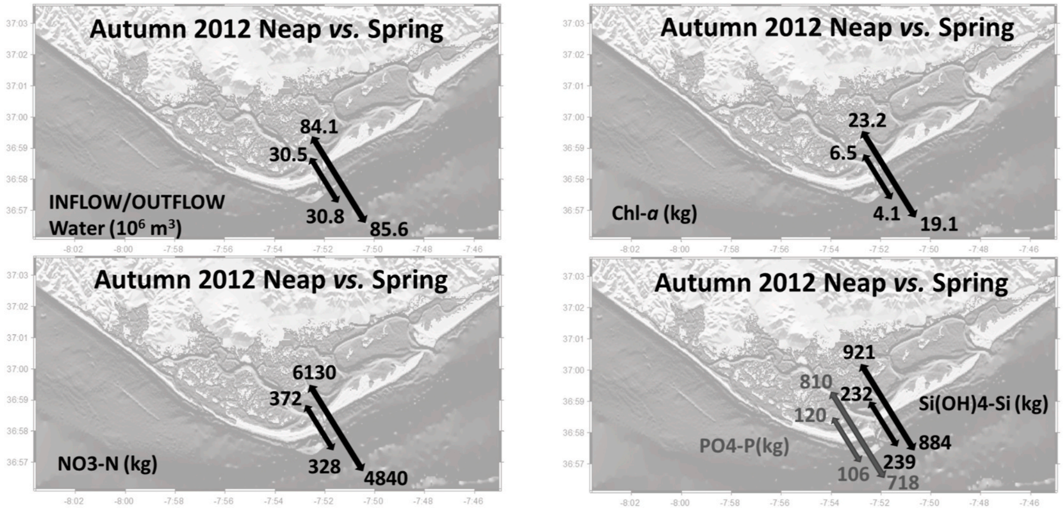

Fig. 5. Transport of water, chlorophyll-a, nitrate, phosphate and silicate (in kg) exchanged between BFO (Faro-Olhão; see Fig. 1 for location) and the adjacent ocean during ebbing and flooding phases along a complete neap tidal (9 October 2012; smallest arrows) and spring tidal cycle (16 October 2012; largest arrows) in Autumn (2012). The landward direction of the arrow indicated an import of matter into Ria Formosa system while the seaward direction of the arrow indicated an export of matter from Ria Formosa.

Table 5
Net exchanges through BFO of water, chlorophyll-a (Chl a), silicate (Si(OH)4), phosphate (PO4), nitrate (NO3), ammonium (NH4) and suspended solids (SS), during Autumn 2012, under neap tide (NT- 9/10/2012) and spring tide (ST- 16/10/2012).

NET Mass exchanges							
Campaign	Water Prism (10^6 m^3)	Chl a (kg)	Si (OH)4 (kg)	PO4 (kg)	NO3 (kg)	NH4 (kg)	SS (t)
NT 09-Oct	−0.3	2.4	−68	14	44	−98	4
ST 16-Oct	−1.5	4.1	371	93	1290	−252	−210

It is clear from this figure that the largest exchanges, either in terms of water or mass of the studied parameters, were recorded at BFO, followed by CF and finally by CO. Between spring and neap tides, as expected, the largest exchanges were found during spring tides. It is important to note that in the last campaign, under spring tide (16 October 2012), as shown in the previous subsection, an upwelling event occurred, which strongly influenced the mass exchange of nitrate, phosphate and silicate, as shown by the highest values (Fig. 6), even if the water volume was not much higher than during the spring tide of Autumn (2011).

One of the features that emerges from this figure is that the residual transport for any of the compounds studied were 1–2 orders of magnitude lower than the transport during ebb or flood. The net volume of water between the inlet and the channels varied between 10^5 and 10^7 m^3. Chl-a, nitrate, phosphate and silicate were net imported (as mentioned in the previous subsection), globally through BFO and both channels, while suspended solids and ammonium were consistently exported from BFO and channels, confirming the previous results for these parameters. From both channels, although CO had higher concentrations than CF (Table SM 3 in SM), the latter exchanged higher net amounts of nutrients, suspended solids and Chl-a (Fig. 6). The individual contribution of the adjacent channels CF and CO in relation to the global amounts exchanged through the main inlet BFO, both in ebb and flood phases, in terms of water volume, Chl a, silicate, phosphate, nitrate, ammonium and suspended solids, during the Autumn campaigns of 2011 and 2012, regardless of spring or neap tides, is shown in Table 6.

The contribution of exchange in terms of water, silicate and suspended solids was higher for CF than for CO in all campaigns (Table 6). However, in some circumstances during ebb and flood, CO contributed to higher exchanges than CF. It is important to note that the contribution of the water volume of the two adjacent channels CF and CO, in relation to the volumes exchanged through BFO, either in ebb or flood periods, was lower than 100%, varying from 60 to 83%, and that the contribution of CF (43–68%) was almost the double of CO (17–26%). It was observed that there was a maximum water volume loss of about 20%. Occasional flood or ebb transport at the channels with contributions greater than 100%, or the sum of the transport contribution of both channels relative to BFO greater than 100%, show that there are other external contributions of these compounds passing through these two channels, higher than those found at BFO.

Considering both flood and ebb periods, it was observed that the dominant direction of water transport was not uniform and changed with time and between the inlet and the channels (Table 7). This was observed between the three main inlets of the western sector of Ria Formosa (Table SM 4 in SM), showing the interconnection between them through the main channels. In fact, CF and CO showed opposite behaviour in terms of water volume exchange between the two tidal cycles and the two successive years (2011 and 2012).

4. Discussion

Hydrodynamic processes such as tides and residual currents at the inlets of coastal lagoons (and estuaries) play an important role in the distribution of dissolved compounds and particulate matter, including planktonic organisms (Lucas et al., 2006), regulating the biological productivity, overall ecological status, and geomorphic processes of these environments (Ferrarin et al., 2016). Mass transport is influenced by internal tidal asymmetry due to bathymetric and topographic effects, but also by wind action and freshwater discharge (Kjerfve and Magill, 1989; Hoitink et al., 2003) as well as other processes interacting simultaneously on the water features of the coastal lagoons transitional environments, affecting the amplitude of their variability. There are, however, limited studies on coupling effects between physical-chemical-biological factors in coastal lagoons (Zainol et al., 2020). Efforts to understand and quantify these transport processes across coastal lagoons have led to an increasing focus on water, salt and nutrient fluxes (Simpson et al., 2001). Some of these works have been reported for some coastal lagoons in the Mediterranean (Sylaios et al., 2006; Giordani et al., 2008; Krasakopoulou and Pagou, 2011; Zainol et al., 2020; Zoidou et al., 2022), Arabic Sea (Kumar et al., 2018; Zhan

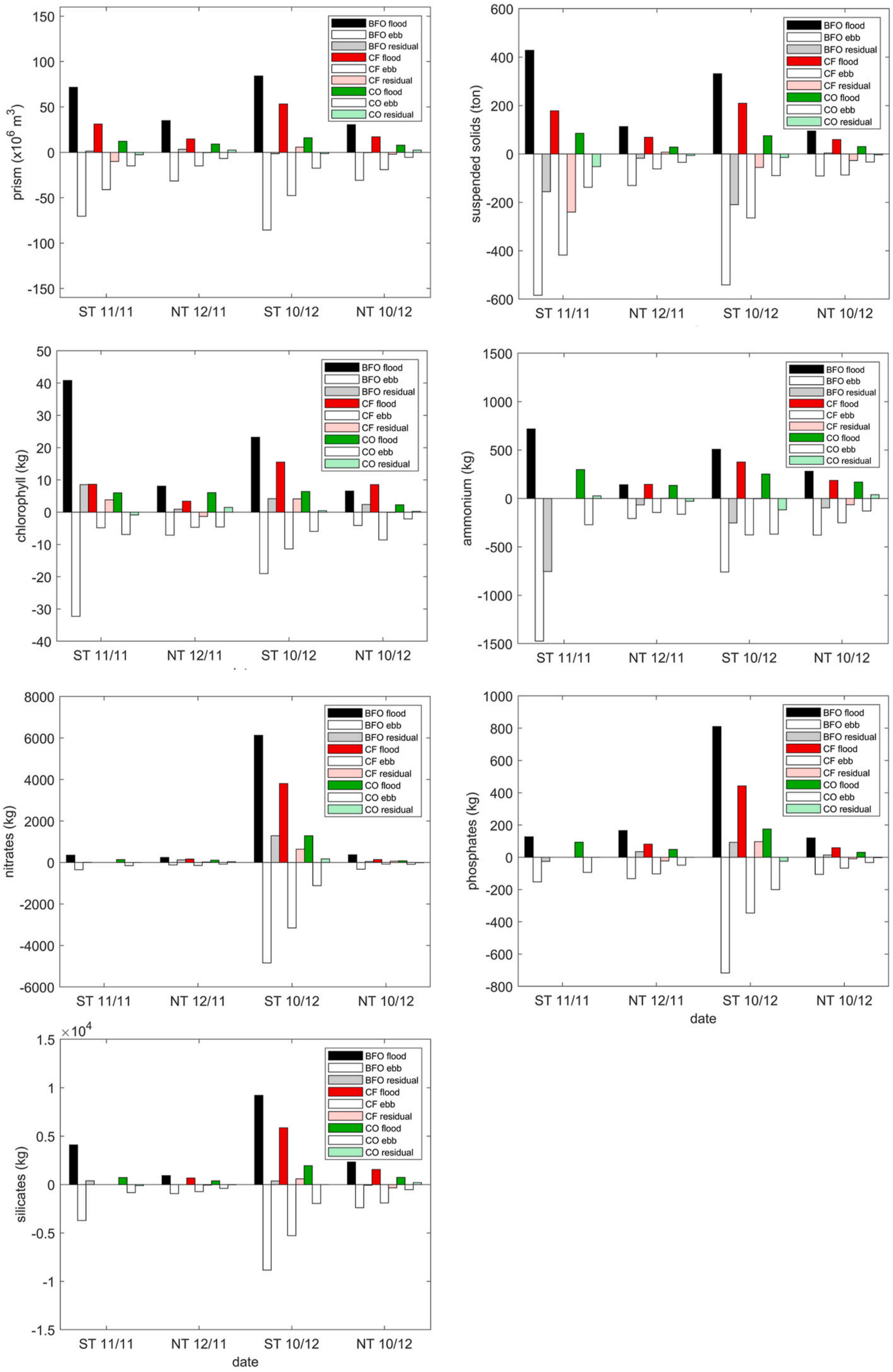

Fig. 6. Water volume exchanged together with the mass exchanges of suspended solids, chlorophyll-a, ammonium, nitrates, phosphates and silicates in Autumn (2011); 2012, under complete spring and neap tidal conditions, illustrating both the flood, ebb and residual exchanges for BFO and adjacent channels: CF (Faro Channel) and CO (Olhão Channel). Solid colour bars (black - BFO, red – CF and green - CO) represent the amounts exchanged during the flood period, the white bar colours represent the amounts exchanged during the ebb period while the net exchanges are represented by the fade colour: grey - BFO, red - CF and green - CO. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

et al., 2022), Brazil (Niencheski and Windom, 1994; Pereira-Filho et al., 2001), Pacific coast of Mexico (Ramírez et al., 2012; Zaytsev and Cervantes-Duarte, 2018) and South China Sea (Li et al., 2014).

This study contributes to fulfil the gap of knowledge that still exists regarding the variability of hydrodynamics and nutrients, Chl-a and suspended solids exchanges through Ria Formosa, a productive coastal lagoon in Southern West Europe. The western sector of Ria Formosa is the most important, accounting for approximately 93% of the total water exchange during each complete tidal cycle (Pacheco et al., 2010). This study was conducted under extreme fortnightly tidal ranges and different seasonal environmental conditions, which strongly modulate the water quality and biological productivity of this ecosystem along the boundary lagoon inlets – adjacent coastal ocean. For the first time, simultaneous discharge measurements coupled with water samples to quantify the concentration of nutrients, Chl-a and suspended solids were used to estimate mass transport through Ria Formosa. This is the most recent research that has jointly assessed: i) the mass budgets through the three main inlets of the western sector; ii) the seasonal pattern of the

Table 6

Individual contribution of the adjacent channels CF and CO in relation to the global amounts exchanged through the main inlet BFO, in both ebb and flood phases in terms of water volume, chlorophyll-a (Chl a), silicate (Si(OH)4), phosphate (PO4), nitrate (NO3), ammonium (NH4) and suspended solids (SS), during Autumn campaigns of 2011 (A-11) and 2012 (A-12), regardless spring or neap tides.

Campaign	Channel	Water prism (10^6 m^3)	Chl a (kg)	Si(OH)4 (kg)	PO4 (kg)	NO3 (kg)	NH4 (kg)	TSS (t)
A-11	CF	43–68%	15–57%	73–78%	49–78%	66–117%	79–95%	42–72%
A-11	CO	17–26%	15–75%	18–42%	30–73%	7–47%	19–95%	20–33%
A-12	CF	56–63%	50–210%	60–79%	48–57%	24–65%	50–74%	49–96%
A-12	CO	18–26%	28–51%	21–31%	28–31%	21–27%	34–60%	17–37%

Table 7

Direction of residual tidal prism through Faro-Olhão Inlet (BFO) and Faro Channel (CF) and Olhão Channel (CO) during the seasonal complete tidal cycles.

Inlet/Channel	Season	Tidal cycle	Residual Prism
BFO	Autumn 2011	ST	Flood
CF	Autumn 2011	ST	Ebb
CO	Autumn 2011	ST	Ebb
BFO	Autumn 2011	NT	Flood
CF	Autumn 2011	NT	Ebb
CO	Autumn 2011	NT	Flood
BFO	Autumn 2012	ST	Ebb
CF	Autumn 2012	ST	Ebb
CO	Autumn 2012	ST	Flood
BFO	Autumn 2012	NT	Ebb
CF	Autumn 2012	NT	Flood
CO	Autumn 2012	NT	Ebb

exchanges occurring through the main inlet and; iii) the role of the main channels adjacent to this main inlet in contributing to the mass balance, as elaborated in the next subsections. This last evaluation comprised Autumn conditions, a productive season, which also included an upwelling pulse. This work also intends to discuss the relative importance of physical processes (tidal, hydrological and meteorological) and impact on chemical and biological processes contributing to the overall exchange between the lagoon and the adjacent coastal water. The role of the hydrodynamics on the mass exchanges through the three main inlets of the western sector of Ria Formosa is discussed below.

4.1. Hydrodynamics and role of the mass exchange of nutrients, chlorophyll-a and suspended solids through the three main inlets of the western sector: effect of tidal conditions under Autumn and Spring conditions

Ria Formosa is a mesotidal system with limited freshwater input, driven from a low precipitation regime, small river and wastewater discharges (Cravo et al., 2014, 2019, 2020, 2022). This contributes to a good vertical mixing, with no significant differences along the water column, as confirmed at inlets and channels, reported in this system (Falcão and Vale, 2003; Newton and Mudge, 2003; Cardoso et al., 2005; Barbosa, 2010; Alcântara et al., 2012; Cravo et al., 2014, 2020; Rosa et al., 2019).

As in other coastal lagoons, Ria Formosa dynamics varied considerably between seasons, mainly dominated by the interaction between the waters inside the lagoon and those in the open sea. The results of this study show the variability of the budgets through the three interconnected inlets during campaigns carried out on three consecutive days in Autumn and Spring seasons. Due to their strong linkage, the variability in one of the inlets is expected to affect the transport at the others, as reported by Pacheco et al. (2010, 2011). BFO is the most important inlet in terms of water exchange and together with BAR represents almost 90% of the total prism (Fig. 3, Table 2). This is in accordance with the magnitude of flood, ebb and net prisms measured by Salles et al. (2005), and Pacheco et al. (2010), that determined 59%–71% for BFO, and 25%–37% for BAR between 2004 and 2007. As reported by Jacob and Cravo (2019), there was a temporal decrease of the net prism at BAN during spring tides (3–4%; Table 2), in comparison with about 5%, reported by Pacheco et al. (2010), due its loss of hydraulic efficiency accompanied by a global increase at BFO and BAR. The direction of the residual prism of the studied inlets (Table SM 4 and Table 7) did not follow the same trend as reported by Salles (2001) and Pacheco et al. (2010), who stated that BFO is a flood dominated inlet, while BAR is an ebb dominated inlet. Nevertheless, the last inlet has lost hydraulic efficiency over time due to a decrease in its width, as reported by Portela (2012). During neap tides, there was a residual transport reduction, and differences between volume exchanges at three inlets in the western sector of Ria Formosa in this study were less pronounced, suggesting that the inlets operate more independently than during spring tides, as suggested by Pacheco et al. (2010). Part of the differences regarding the direction of the residual prism among the campaigns of this study and between the campaigns led by other authors may be related to the variability of the tidal periods considered, since the duration of successive tidal cycles along three days was not the same, nor were the initial phases of the tides exactly the same, together with possible hydrodynamic changes that may have occurred due to the interconnection of the two natural inlets (Ancão and Armona) of the western sector of the Ria Formosa, as already pointed out by Rosa et al. (2019).

The contribution of each of the three inlets to the total amount exchanged through the western sector of Ria Formosa in terms of Chl-a, suspended solids and nutrients during the Autumn and Spring seasons did not follow the same trend as the water volume (Table 2), demonstrating that these compounds do not behave conservatively. As expected, the magnitude of mass exchange of these compounds during flood and ebb was highest at BFO, due to the maximum discharge associated with the largest cross-sectional area of this inlet (Table 1) and more intense current velocity (Jacob and Cravo, 2019), as the range of concentrations between inlets were similar in each campaign (Table SM 1 in SM). Between tidal conditions, net exchanges (Table 3) were particularly higher during the spring tide due to the highest volume of water exchanged, also corresponding to the lowest residence time and the lowest intensity of biological processes. Exchanges were globally higher during the Spring campaign, in response to the different phytoplankton growth between the two seasons. This is supported by the Hovmöller diagram of averaged MODIS-Aqua chlorophyll-a from one year, July 2011 to July 2012, along a stretch from 7.75°W to 8°W off the southern coast of Portugal, averaged between 36.8°N and 36.9°N (Fig. 7). There was an increase in Chl-a import during the March campaign, reflecting the increase in phytoplankton, apparently not associated with upwelling (Fig. SM 2 in SM), but due to the development of a typical spring bloom in front of the coast of Ria Formosa, entering through its inlets, which was recorded between March and mid-April 2012 (>1 mg/m^3), but not observed during the neap tide in May 2012 (0.3–0.5 mg/m^3), corresponding to a post-bloom period. The phytoplankton activity during the Autumn campaign was low, corresponding to low Chl-a values (<0.3 mg/m^3; Fig. 7). In fact, only a unimodal spring bloom was observed that year, as was found in the previous three years, demonstrated in Cravo et al. (2014). This is in agreement with the results of Winder and Cloern (2010), who found that the dominance and recurrence strength of spring phytoplankton blooms from temperate and subtropical zones correspond to about 50% of the cases, while both

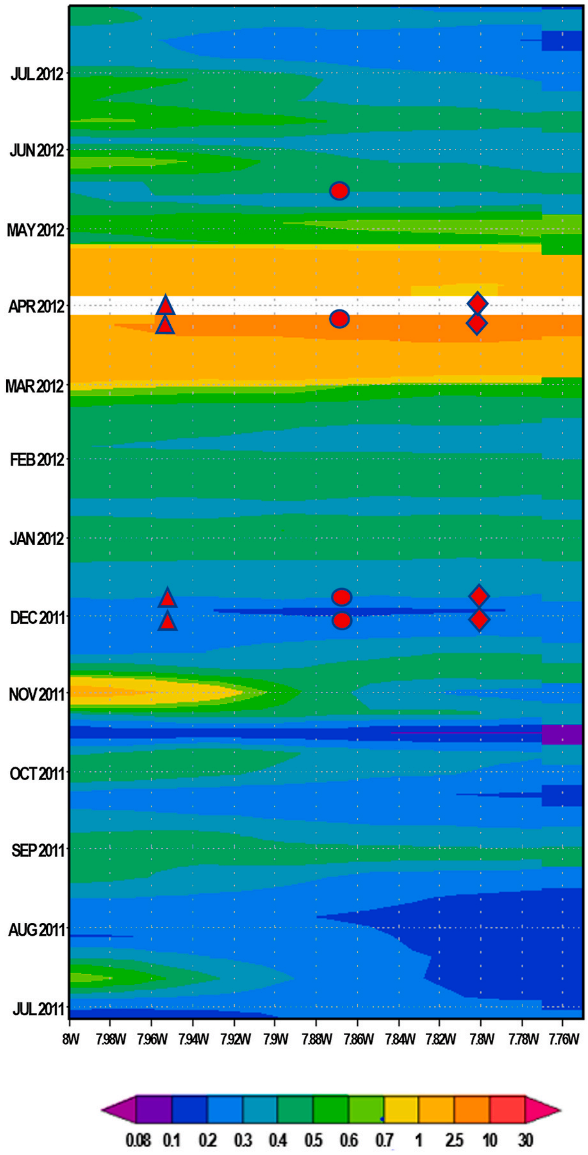

Fig. 7. Hovmöller diagram of 8-day (4 km) averaged MODIS-Aqua chlorophyll-a for a complete year from July 2011 to July 2012, covering the six field surveys along a section 7.75°W to 8°W off the Portuguese southern coast, averaged between 36.8° N and 36.9° N, generated by the NASA Giovanni website, including the three studied inlets area in the period considered. The red symbols represent the inlets in the field surveys date. BAN = triangle; BFO = circle, BAR = diamond. Source: Ocean Colour, NASA. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

spring and autumn blooms correspond to barely 20%. The maximum import of Chl-a in March 2012, under the spring tide, led to the fertilisation of the Ria Formosa, also accompanied by an import of nitrate and silicate. Concurrently, there was a fertilisation of the adjacent coast with phosphate, ammonium and suspended solids (about 20% organic, as characterised by Rosa et al., 2019), through a net export of these compounds, considering that Ria Formosa, being more productive than offshore and promoting high rates of remineralisation of organic matter, can provide higher concentrations of these compounds to the adjacent coastal ocean. However, it can also be shown that, given the productivity of this shallow system, during periods of rapid phytoplankton growth, the consumption of nitrate and silicate may be higher than in the ocean, resulting in an import of these nutrients, more detailed in the next subsection. Between the three inlets, the direction of net exchanges (Table 3) was not always the same, but varied between tidal conditions and seasons, reinforcing the idea of a high connectivity between them. However, the fact that the direction of net exchange was occasionally the same between the three inlets may also be related to the fact that the campaigns were not carried out simultaneously due to logistical constraints, but on three consecutive days.

4.2. *Effect of seasonal variability at the main inlet of Ria Formosa on phytoplankton growth, under spring tidal conditions*

The net water import/export through the BFO, maximised during the spring tidal cycles, was shown to vary seasonally in response to physical processes (meteorology/hydrology), as reinforced by wind stress and satellite imagery (Figs. SM 1-6 in SM), highlighting the need for frequent sampling around the year, as mentioned by other authors (Nieblas et al., 2009; Hayn et al., 2014). However, some of the differences between the seasonal campaigns in spring tides may also be related to differences in tidal height and/or cross-sectional area sampled (Table 1). In the case of Chl-a and nutrients, their transport was also mediated by phytoplankton growth, which increases during Spring affects the nutrients cycles through their consumption (Paerl et al., 2006); by land runoff associated with precipitation and by upwelling events. These results showed the influence of the exchanges through Ria Formosa, acting as a sink or source of material, as detailed below.

During spring tides, BFO consistently exported suspended solids and ammonium, as mentioned in the previous subsection, confirming the heightened biological processes in this shallow environment compared to the coastal area off Ria Formosa, thus fertilising the coast, as found by Malta et al. (2017). The net transport of suspended solids during the Autumn 2011; 2012 and Winter campaigns (Tables 4 and 5), assuming 20% of these are organic (as previously mentioned), would correspond to an important source of 30–40 tonnes of organic matter, fertilising the coastal zone along with a source of ammonium during the ebb of the Autumn campaign (1470 kg; Fig. 4).

The importance of local meteorological conditions that induce precipitation (and thus freshwater input) and upwelling are also reported in other coastal lagoons (Roselli et al., 2013; Mahanty et al., 2016; Barros et al., 2017; Zaytsev and Cervantes-Duarte, 2018). Under the extreme meteorological events, after a period of rainfall (about 44 mm in the 10 days preceding the Winter campaign) and during the (dry) Summer campaign, there was a supply of nutrients to the coast. During the Winter campaign, the increased land runoff can lead to a net export of water, suspended solids, organic matter, nutrients and Chl-a (a small amount) to the coast. A significant increase of nitrate and phosphate, and suspended solids concentrations (along with a decrease in dissolved oxygen and salinity; Table SM 2 in SM) after a rainfall period during the Winter campaign at BFO, was also reported by Newton and Mudge (2005) and Malta et al. (2017) for Ria Formosa, as well as for some microtidal lagoons. In particular, this was also found in Greece, where three lagoons received nutrients from agricultural drainage, which were partly exported to the coastal waters during ebb period (Zoidou et al., 2022), like in the Vassova lagoon (Sylaios et al., 2006), and for two coastal lagoons, on the east coast of the Gulf of California (Medina-Galván et al., 2021). It is known that nutrients and sediments are always flushed from land during hydrologically active periods, such as the rainy season (Arhonditsis et al., 2002; Chen et al., 2015 and references therein; Dybowski and Dzierzbicka-Głowacka, 2023).

During the Summer campaign, the magnitude of exchanges (including suspended solids) was the lowest, except for phosphate. This could be explained by a continuous consumption by phytoplankton since the spring season, which was particularly exacerbated during a period of reduced freshwater input and/or land runoff. Nevertheless, there was an overall export of compounds, contrary to the import tidal prism. During this season, the coastal waters, under the influence of a warm coastal countercurrent from the Gulf of Cadiz (Fig. SM 5 in SM), are usually poor in nutrients and chlorophyll-a (Navarro et al., 2006), compared to the waters inside the Ria Formosa. These are more productive than offshore, leading to an overall net export, indicating that the Ria Formosa is a source of nutrients, Chl-a and suspended solids to the coast, contributing to increase the biological productivity of the neighbouring coastal zone. Within this shallow lagoon (due to internal recycling of organic matter), the decomposition rate could be faster during summer due to increased bacterial activity under increasing water temperature (Medina-Galván et al., 2021; Puppin et al., 2023), providing nutrients to this system, as observed for the maximum net export of silicate (1040 kg; Table 4). It is important to note that the highest phosphate exchange resulted from the maximum concentration found during this campaign (Table SM 2 in SM), which may result from increased desorption from sediments under increases of water temperature during this season (Nixon, 1982; Ruardij and Van Raaphorst, 1995; Peng et al., 2021). These findings were already reported by Rosa et al. (2019) and documented for benthic fluxes studies conducted in this system (Falcão and Vale, 1998; Serpa et al., 2007).

Episodic upwelling events supplied nutrients, especially nitrate, from the coast to the Ria Formosa (Tables 4 and 5), that can also be associated with low phytoplankton consumption and nitrification during periods of low temperature, as in the Winter campaign, which will ultimately affect phytoplankton growth. The combined upwelling-tidal effect is a complex dynamic process, subject to high temporal variability and difficult to predict (Zaytsev and Cervantes-Duarte, 2018). However, it is known that when coastal upwelling occurs, nutrients transfer rates from the sea to the lagoons are the highest of the year, with the coastal lagoons acting as sinks for nutrients. Upwelling along the southern coast of Portugal is not permanent, although it is more frequent between April and September (Relvas and Barton, 2002), under favourable westerly winds. The Chl-a variability, which expresses the phytoplankton activity during these events, depended on the phase of the upwelling, as reported by Simons and Catlett (2023) for an upwelling region in the Santa Barbara Channel, California. These authors indicate three phases: (i) the upwelling initiation and subsequent increase in strength, (ii) the transition phase, when the upwelling changes from increasing to decreasing strength, and (iii) the relaxation phase, when the upwelling strength decreases until the end of the upwelling period). They found that Spring Chl-a is regulated by the coupling of upwelling and (eddy) circulation, and that elevated Spring Chl-a requires the presence of both high nitrate, provided by upwelling, and long residence time, also dependent on wind relaxation. The Winter and Autumn 2012 campaigns were influenced by upwelling (Figs. SM 4 and SM 3 in SM, respectively), but apparently captured in different phases. During the Winter campaign, in mid-March, the upwelling event was captured at the beginning (Figs. SM 4 and SM 6, bottom panel, in SM), when there was a net import, especially of nitrate (750 kg; Table 4). It is known that during the vertical movement of water rising from deeper levels, phytoplankton development is not favoured (Wilkerson et al., 2006) and during this campaign a net export of Chl-a from Ria Formosa was estimated (13.8 kg; Table 4). However, about 2 weeks after this sampling, in the first week of April, upwelling conditions persisted and then relaxed (Fig. SM 6, bottom panel, in SM). The following steadiness of the water column could have favoured phytoplankton growth, which could have driven the increase in Chl-a along the south and southwest coast (Fig. SM 4 in SM). This could also match the typical Spring bloom period, as observed in the last 4 years (see Fig. 6A in Cravo et al., 2014). During the Autumn 2012 campaign, a stronger upwelling episode was captured under spring tidal conditions, under stronger westerly winds, accompanied by a decrease in water temperature recorded by the PT deployed in Ria Formosa and a higher inshore-offshore water temperature gradient (Fig. SM 6, bottom panel, in SM), with a decrease in temperature off Ria Formosa compared to the neap tide sampled the previous week. During this campaign, there was a net export of water, but a net import of Chl-a (4 kg) and all nutrients, especially a net import of nitrate of more than 1 ton (6 tons during the flood *vs.* 4.8 tons during the ebb, Fig. 5; Table 5), corresponding to the campaign when the imported amounts were the highest, thus fertilising the Ria Formosa. At this time, the Chl-a exchange in flood and ebb periods increased almost 4 times compared to the previous week (Fig. 5), confirming that the upwelling was in an advanced phase, starting the relaxation period (Fig. SM 6, bottom panel, in SM) and stimulating phytoplankton growth along the southern coast of Portugal, as confirmed by satellite imagery (Fig. SM 3 in SM). A particular import of nitrate during upwelling events has been reported by several authors for the Ria Formosa (Falcão and Vale, 2003; Newton and Mudge, 2005; Loureiro et al., 2006; Brito et al., 2010; Alcântara et al., 2012; Cravo et al., 2014, 2019; Rosa et al., 2019), as well as for other lagoons affected by upwelling such as the coastal lagoons on the east coast of the Gulf of California (Medina-Galván et al., 2021) and the Magdalena Lagoon on the Mexican Pacific coast (Cervantes-Duarte et al., 2013; Zaytsev and Cervantes-Duarte, 2018).

The Spring and Autumn campaigns at BFO showed similar import and export trends: import of Chl-a, nitrate and silicate and export of suspended solids, ammonium and phosphate (Table 4). Still, the spring phytoplankton bloom in March 2012 increased the maximum net import of Chl-a (*ca.* 24 kg; Table 4) and nitrate (Fig. 4; 572 kg; Table 4), contributing to the enhancement of primary production in Ria Formosa. This means that the nutrient budgets also depend on the assimilation rate by phytoplankton either on the coast or inside Ria Formosa. Increased nutrient assimilation associated with higher primary production in a shallow system like Ria Formosa, as found during the Spring campaign, or under upwelling, or even during the Autumn campaigns, made the lagoon a sink for nutrients due to their import. Nevertheless, the mass transport was not consistent between all the parameters studied, especially between N and P nutrients (Table 4), as found at BFO by Rosa et al. (2019), using a similar contemporary seasonal approach, or by Malta et al. (2017), or in other coastal lagoons (Giordani et al., 2008; Krasakopoulou and Pagou, 2011; Hayn et al., 2014). It was found that nutrients import during the Spring (and Autumn) did not follow exactly the same trends as found by Falcão and Vale (2003) and Newton and Mudge (2005) in Ria Formosa during spring tides. However, these authors quantified the concentration differences between high tide (inflowing seawater) and low tide (outflowing lagoon water) and calculated the water volumes exchanged through Ria Formosa during each tidal cycle but did not measure either the currents or the discharge through each inlet. In addition, as mentioned in the previous subsection, some hydrodynamic changes have occurred over time at the inlets of the western sector, which may alter the mass exchanges.

Comparing the magnitude of mass exchanges with that estimated in other studies, the DIN exchanges in this study were lower than those calculated by Malta et al. (2017) for BFO, which may be due to the fact that these authors used a different approach to calculate mass exchanges. They did not measure the discharge, but used the discharge estimated by Pacheco et al. (2010). The DIN exchange was also lower than that estimated by Zaytsev and Cervantes-Duarte (2018) in the Magdalena Lagoon on the Mexican Pacific coast, which has a much larger cross-sectional area and consequently a higher discharge. In this mesotidal system, tidal exchange and residual velocities are enhanced compared to microtidal lagoons, such as those found in the Mediterranean, where tidal effects appear to be the dominant factor controlling transport into and out of lagoons, followed by wind stress (Sylaios et al., 2006; Zoidou et al., 2022).

4.3. *Interconnectivity between the main inlet and the adjacent channels particularly in autumn conditions (2011–2012)*

There is a strong hydrodynamic interconnectivity between the main inlet and the adjacent channels. As reported by Pacheco et al. (2010), the three inlets act as a hydrodynamic subsystem, with the excess flood prism at BFO flowing through BAN via CF, while flowing through BAR via CO. Fabião et al. (2016) also confirmed that CO receives an important contribution from BAR, while CF from BAN. The pattern of interconnectivity between BFO, CF and CO in this study was not consistent between the Autumn 2011; 2012 campaigns, and varied between neap and spring tidal conditions, being maximised during spring tides, as expected, for the reason already mentioned (Fig. 6). The direction of the net tidal prism through the BFO and adjacent channels (Table 7) differed from the results of other authors who studied the behaviour of the adjacent channels of the BFO in the early 2000s (Ventura Soares et al., 2001; Pacheco et al., 2010, 2011). In this work, the CF was the most important channel in terms of water exchange with respect to BFO, up to 68% for both flood and ebb, while CO only contributed up to 26% (Table 6). This is discrepant with Pacheco et al. (2010), who found that the pattern of circulation through BFO during flood is mainly through CO, while during ebb it is through CF, with a recirculation pattern through the secondary channels connecting the two main channels. The spatial and temporal differences found in this work could be attributed to the points mentioned at the end of section 4.1. Meanwhile, the contribution of CF to BFO during flood and ebb was slightly lower than the values reported by Ventura Soares et al. (2001), who found that CF (with stronger currents) contributed from 72 to 76% to BFO, while the Cais do Carvão, in CO, contributed from 24 to 28%, a value similar to the one found in this work (Table 6).

For both CO and CF, there was a global export of suspended solids and ammonium under autumn conditions, as for the three interconnected inlets of the western sector of Ria Formosa, confirming that this shallow lagoon is a source of these compounds. The exchange contribution of water and other compounds was higher for CF than for CO in all campaigns due to its higher tidal prism (Fig. 6), although CO has higher nutrient concentrations. The CF is well defined, deeper and narrower than the CO (Fig. 1; see Table 1). The latter is less defined and shallower, with an extensive area of salt marsh in the vicinity (Fig. 2), where a higher volume of water may be dispersed over salt marshes during flood, not totally accounted for the discharge calculation on the sectional area, leading to a water loss of maximum about 20%. In addition, CO, located east of BFO, includes an area under the influence of preferential circulation of water from north (Fig. 2), passing from Esteiro da Garganta, where effluents from the wastewater treatment plant are discharged (Cravo et al., 2015, 2022), flowing towards Esteiro dos Cações and then towards BFO, as confirmed by a hydrodynamic model developed for Ria Formosa (Fabião et al., 2016). This circulation pattern, together with the remineralisation of organic matter with accumulation intensified in salt marshes (Puppin et al., 2023) and/or in secondary channels, may have enhanced diffusive fluxes from the sediments, over a large area with shellfish beds (Fig. 2), which may be responsible for some increase in the CO contribution to nutrient and Chl-a exchanges. This fact may also support occasional flood or ebb transport at the channels with contributions greater than 100%, or the sum of the transport contribution of both channels relative to BFO was greater than 100%, showing that there are other external sources contributing to these compounds passing through these two channels, at concentrations higher than those found at BFO.

Knowledge of water circulation patterns and exchanges between inlets and channels in coastal lagoons is also crucial for the sustainable management of these systems (Zoidou et al., 2022). Indeed, tidal channel management and comprehensive understanding of mass exchanges are critical issues for maintaining the ecosystem services provided by coastal lagoons such as Ria Formosa. Regardless some knowledge on hydrodynamics at BFO and adjacent channels exists (Salles, 2001; Salles et al., 2005; Pacheco et al., 2010, 2011; Jacob and Cravo, 2019) little is known about the magnitude and importance of mass exchanges on nutrients, Chl-a, and suspended solids passing there. This may be particularly important for the management of shellfish production, a resource that is highly dependent on water quality, which is more concentrated around CO than at CF (Fig. 2). Thus, control measures such as channel dredging or deepening to improve water circulation and water quality through increased renewal are of great importance. The capability to make accurate predictions emerges as a critical factor for the success of coastal management and conservation in a rapidly changing world (Little et al., 2017), especially in a productive system such as Ria Formosa.

5. Conclusions

When considering the three inlets of the western sector of Ria Formosa, BFO stands out as the most important regarding mass exchanges, which are intensified during spring tides with maximum discharges. BAN showed the lowest mass exchanges, accounting only 3–4% of water mass.

The Spring campaign showed enhanced mass exchanges, when a spring phytoplankton bloom was captured, with an important mass import of chlorophyll-a and nitrate. However, there was a general net export of ammonium and suspended solids that was fertilising the adjoining ocean, supporting its biological productivity and showing that Ria Formosa was a source of these compounds.

At the main inlet, BFO, the mass exchanges changed seasonally under spring tides. Extreme meteorological events (rainfall, upwelling or dry summer conditions) are shown to be the dominant factors explaining mass exchanges rather than tides. Following a period of rainfall, there was a net export of water and of all compounds, except nitrate and phosphate. These were still imported due to the concurrent influence of a week upwelling event. However, under the influence of a more intense upwelling event during the Autumn 2012 campaign, the import of nitrate was further intensified and contributed with a net import of about 1.3 tons. During the Summer campaign, under the influence of a coastal countercurrent recirculating from the Gulf of Cadiz, despite the magnitude of the flood and ebb exchanges were relatively low, there was a global supply of compounds, regardless of the opposite direction of the tidal prism, indicating that Ria Formosa acted as a source of material, contributing to increase the productivity of the coastal zone, especially in a period when these waters are typically oligotrophic. Nevertheless, during the Summer campaign, the maximum net export of silicate was estimated (1 ton), exceeding that of the Winter campaign (approximately 640 kg). During the Spring and Autumn campaigns, there was an import of chlorophyll-a, nitrate and silicate, demonstrating that Ria Formosa also depends on the interconnected coastal zone to be fertilised and increase its productivity in this shallow system where nutrient consumption by phytoplankton is faster than offshore.

The connectivity of the main inlet with the other two is established by two adjacent channels, with CF being the most important regarding mass exchange. Nevertheless, higher chlorophyll-a and N and P nutrient concentrations were found at CO, due to external sources such as salt marshes, shellfish beds and perhaps with some contribution from the wastewater treatment plant.

Ria Formosa is a highly dynamic tidal system presenting a strong linkage between physical and biogeochemical processes between the tidal inlets, major channels and the adjacent ocean. The magnitude of the exchanges and differences between tides, seasons and years is due not only to tidal ranges, which are not exactly the same even within the same tidal phase, but also to meteorological, oceanographic and biological processes. Biogeochemical and physical processes interact over several timescales (short-term to long-term) and on spatial scales (from millimeters to kilometers) driving variability in water quality features. The local drivers in coastal systems can make it particularly difficult to predict under a context of global changes. Timely, accurate, and consistent scientific-based assessments, monitoring and forecasting of water quality and estimation of mass exchanges are crucial across global, regional, and local scales.

Data from this study could be used as a reference, particularly important for management of Ria Formosa, a productive system where bivalves production depends deeply on water quality, its renewal and exchanges with the ocean. More similar works to estimate exchanges between Ria Formosa and the adjacent ocean are needed to consolidate these results and establish more robust trends and/or specific behaviours that can govern long-term trends and ultimately be compared with future conditions in a changing world and be transferred to similar systems either meso- or microtidal.

CRediT authorship contribution statement

Alexandra Cravo: Writing – original draft, Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis. **José Jacob:** Writing – original draft, Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis. **Alexandra Rosa:** Writing – review & editing, Investigation, Formal analysis. **Cátia Correia:** Writing – review & editing, Investigation, Formal analysis.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

All the authors reports administrative support was provided by University of Algarve Centre for Marine and Environmental Research. All the authors reports financial support was provided by Foundation for Science and Technology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2024.108987.

Data availability

Data will be made available on request.

References

Alcântara, P., Cravo, A., Jacob, J., 2012. Variability of nutrients and chlorophyll a in Ancão Inlet during a spring tidal cycle in April 2009. Cienc. Mar. 38 (April 2009), 161–176. https://doi.org/10.7773/cm.v38i1B.1780.

Allen, G., Mandelli, E., Zimmermann, J.P.F., 1981. Physics, geology, chemistry. In: Lasserre, P., Postma, H. (Eds.), Coastal Lagoon Research, Present and Future: Proceedings of a Seminar. United Nations Educational, Scientific, and Cultural Organization, Paris, France, pp. 29–50. UNESCO Technical Papers in Marine Science 32.

Anthony, A., Atwood, J., August, P., Byron, C., Cobb, S., Foster, C., Fry, C., Gold, A., Hagos, K., Heffner, L., Kellogg, D.Q., Lellis-Dibble, K., Opaluch, J.J., Oviatt, C., Pfeiffer-Herbert, A., Rohr, N., Smith, L., Smythe, T., Swift, J., Vinhateiro, N., 2009. Coastal lagoons and climate change: ecological and social ramifications in U.S. Atlantic and Gulf coast ecosystems. Ecol. Soc. 14 (1), 8. https://doi.org/10.5751/ES-02719-140108.

Artioli, Y., Friedrich, J., Gilbert, A.J., McQuatters-Gollop, A., Mee, L.D., Vermaat, J.E., Wulff, F., Humborg, C., Palmeri, L., Pollehne, F., 2008. Nutrient budgets for European seas: a measure of the effectiveness of nutrient reduction policies. Mar. Pollut. Bull. 56, 1609–1617. https://doi.org/10.1016/j.marpolbul.2008.05.027.

Arhonditsis, G., Tsirtsis, G., Karydis, M., 2002. The effects of episodic rainfall events to the dynamics of coastal marine ecosystems: applications to a semi-enclosed gulf in the Mediterranean Sea. J. Mar. Syst. 35, 183–205. https://doi.org/10.1016/S0924-7963(02)00081-7.

APHA, A., 2002. WPCF, Standard Methods for the Examination of Water and Wastewater. Amer. Public Health Assoc., Washington, DC.

Barbosa, A.B., 2010. Seasonal and interannual variability of planktonic microbes in a mesotidal coastal lagoon (Ria Formosa, SE Portugal): impact of climatic changes and local human influences. In: Paerl, H., Kennish, M. (Eds.), Coastal Lagoons: Critical Habitats of Environmental Change. CRC Press, Taylor & Francis Group, Marine Science Book Series, Boca Raton, pp. 335–366.

Barros, G. de, Fonseca, A.L.D., Santos, A.C. dos, Fozvntes, M.L.S., Varela, A.R.D., Franco, D., 2017. Nutrient distribution in a shallow subtropical lagoon, south Brazil, subjected to seasonal hypoxic and anoxic events. Braz. J. Oceanogr. 65 (2), 116–127. https://doi.org/10.1590/S1679-87592017101206502.

Brito, A.C., Newton, A., Tett, P., Fernandes, T.F., 2010. Sediment and water nutrients and microalgae in a coastal shallow lagoon, Ria Formosa (Portugal): implications for the water framework directive. J. Environ. Monit. 12, 318–328. https://doi.org/10.1007/s12237-016-0150-9.

Buzzelli, C., Wan, Y., Doering, P.H., Boyer, J.N., 2013. Seasonal dissolved inorganic nitrogen and phosphorus budgets for two subtropical estuaries in south Florida, USA. Biogeosciences 10, 6721–6736. https://doi.org/10.5194/bg-10-6721-2013.

Cardoso, A., Santos, A., Cruz, I., 2005. A Ria Formosa – uma visão global da química das águas e sedimentos, 17. ANAIS do Instituto Hidrográfico, pp. 2003–2004, 7-12. (in Portuguese).

Cervantes-Duarte, R., Prego, R., López-López, S., Aguirre-Bahena, F., Ospina-Alvarez, N., 2013. Annual patterns of nutrients and chlorophyll in a subtropical coastal lagoon under the upwelling influence (SW of Baja-California Peninsula). Estuar. Coast Shelf Sci. 120, 54–63. https://doi.org/10.1016/j.ecss.2013.01.020.

Chapman, P.M., 2012. Management of coastal lagoons under climate change. Estuar. Coast Shelf Sci. 110, 32–35. https://doi.org/10.1016/j.ecss.2012.01.010.

Chen, Y., Song, X., Zhang, Z., Shi, P., Tao, F., 2015. Simulating the impact of flooding events on non-point source pollution and the effects of filter strips in an intensive agricultural watershed in China. Limnol 16, 91–101. https://doi.org/10.1007/s10201-014-0443-2.

Cravo, A., Cardeira, S., Pereira, C., Rosa, M., Alcântara, P., Madureira, M., Rita, F., Luis, J., Jacob, J., 2014. Exchanges of nutrients and chlorophyll a through two inlets of Ria Formosa, South of Portugal, during coastal upwelling events. J. Sea Res. 93, 63–74. https://doi.org/10.1016/j.seares.2014.04.004.

Cravo, A., Fernandes, D., Damião, T., Pereira, C., Reis, M.P., 2015. Determining the footprint of sewage discharges in a coastal lagoon in South-Western Europe. Mar. Pollut. Bull. 96, 197–209. https://doi.org/10.1016/j.marpolbul.2015.05.029.

Cravo, A., Cardeira, S., Pereira, C., Rosa, M., Alcântara, P., Madureira, M., Rita, F., Correia, C., Rosa, A., Jacob, J., 2019. Nutrients and chlorophyll-a exchanges through an inlet of the Ria Formosa lagoon, SW Iberia during the productive season –unravelling the role of the driving forces. J. Sea Res. 144, 133–141. https://doi.org/10.1016/j.seares.2018.12.001.

Cravo, A., Rosa, A., Jacob, J., Correia, C., 2020. Dissolved oxygen dynamics in Ria Formosa lagoon (South Portugal) - a real time monitoring station observatory. Mar. Chem. 223, 1–14. https://doi.org/10.1016/j.marchem.2020.103806.

Cravo, A., Barbosa, A.B., Correia, C., Matos, A., Caetano, S., Lima, M.J., Jacob, J., 2022. Unravelling the effects of treated wastewater discharges on the water quality in a coastal lagoon system (Ria Formosa, South Portugal): relevance of hydrodynamic conditions. Mar. Pollut. Bull. 174, 113296. https://doi.org/10.1016/j.marpolbul.2021.113296.

Dybowski, D., Dzierzbicka-Głowacka, L., 2023. Analysis of the impact of nutrients deposited from the land side on the waters of Puck Lagoon (Gdańsk Basin, Southern Baltic): a model study. Oceanol 65 (2), 386–397. https://doi.org/10.1016/j.oceano.2022.11.005.

Fabião, J., Rodrigues, M., Fortunato, A.B., Jacob, J., Cravo, A., 2016. Water exchanges between a multi-inlet lagoon and the ocean: the role of forcing mechanisms. Ocean Dynam. 66 (2), 173–194. https://doi.org/10.1007/s10236-015-0918-7.

Falcão, M., Vale, C., 1998. Sediment–water exchanges of ammonium and phosphate in intertidal and subtidal areas of a mesotidal coastal lagoon (Ria Formosa). Hydrobiol. (Sofia) 373/374, 193–201. https://doi.org/10.1007/978-94-011-5266-2_16.

Falcão, M., Vale, C., 2003. Nutrient dynamics in a coastal lagoon (Ria Formosa, Portugal): the importance of lagoon–Sea Water exchanges on the biological productivity. Cienc. Mar. 29, 425–433.

Ferrarin, C., Umgiesser, G., Roland, A., Bajo, M., De Pascalis, F., Ghezzo, M., Scroccaro, I., 2016. Sediment dynamics and budget in a microtidal lagoon—a numerical investigation. Mar. Geol. 381, 163–174. https://doi.org/10.1016/j.margeo.2016.09.006.

Giordani, G., Austoni, M., Zaldívar, J.M., Swaney, D.P., Viaroli, P., 2008. Modelling ecosystem functions and properties at different time and spatial scales in shallow coastal lagoons: an application of the LOICZ biogeochemical model. Estuar. Coast Shelf Sci. 77, 264–277. https://doi.org/10.1016/j.ecss.2007.09.017.

Grasshoff, K., Erkhardt, M., Kremling, K., 1999. Methods of Seawater Analysis. Third, Completely Revised and Extended Edition. Wiley-VCH, New York, p. 598.

Hayn, M., Howarth, R., Marino, R., Ganju, N., Berg, P., Foreman, K.H., Giblin, A.E., McGlathery, K., 2014. Exchange of nitrogen and phosphorus between a shallow lagoon and coastal waters. Estuar. Coast 37, S63–S73. https://doi.org/10.1007/s10533-023-01083-2.

Hoitink, A.J.F., Hoekstra, P., Van Maren, D.S., 2003. Flow asymmetry associated with astronomical tides: implications for the residual transport of sediments. J. Geophys. Res. 108. https://doi.org/10.1029/2002JC001539 n. C10, 3315.

IH, 2000. Relatório de Progresso dos Trabalhos, Rel. PT. 0606/2000 Monitorização Ambiental da Ria Formosa 1999. Instituto Hidrográfico. Technical Report, p. 24 (in Portuguese).

Jacob, J., Cravo, A., 2019. Recent evolution of the tidal prisms at the inlets of the western sector of the ria Formosa, south coast of Portugal. Reg. Stud. Mar. Sci. 31, 100767. https://doi.org/10.1016/J.RSMA.2019.100767.

Kjerfve, B., Magill, K.E., 1989. Geographic and hydrodynamic characteristics of shallow coastal lagoons. Mar. Geol. 88, 187–199. https://doi.org/10.1016/0025-3227(89)90097-2, 1989.

Krasakopoulou, E., Pagou, K., 2011. Seasonal steady-state budgets of nutrients and stoichiometric calculations in an eastern Mediterranean lagoon (Papas lagoon-Greece). Mediterr. Mar. Sci. 12, 21–41. https://doi.org/10.12681/mms.51.

Kumar, P.S., Kumaraswami, M., Rao, G.D., Ezhilarasan, P., Sivasankar, R., Rao, V.R., Ramu, K., 2018. Influence of nutrient fluxes on phytoplankton community and harmful algal blooms along the coastal waters of southeastern Arabian Sea. Continent. Shelf Res. 161, 20–28. https://doi.org/10.1016/j.csr.2018.04.012.

Li, R.H., Liu, S.M., Li, Y.W., Zhang, G.L., Ren, J.L., Zhang, J., 2014. Nutrient dynamics in tropical rivers, lagoons, and coastal ecosystems of eastern Hainan Island, South China Sea. Biogeosciences 11, 481–506. https://doi.org/10.5194/bg-11-481-2014.

Little, S., Spencer, K.L., Schuttelaars, H.M., Millward, G.E., Elliott, M., 2017. Unbounded boundaries and shifting baselines: estuaries and coastal seas in a rapidly changing world. Estuar. Coast Shelf Sci. 198, 311–319. https://doi.org/10.1016/j.ecss.2017.10.010.

Lobo, M., Loureiro, D., Nepomuceno, A., Alves, L., Lamego, F., 2023. Phosphorus spatial distribution and mass balance in the Itaipu lagoon (Rio de Janeiro, Brazil). Ocean and Coastal Research v71, e23012. https://doi.org/10.1590/2675-2824071.21092ml, 2023.

Lorenzen, C., 1967. Determination of chlorophyll and pheopigments: spectrophotometric equations. Limnol. Oceanogr. 12, 343–346. https://doi.org/10.4319/lo.1967.12.2.0343.

Loureiro, S., Newton, A., Icely, J., 2006. Boundary conditions for the European water framework directive in the Ria Formosa lagoon, Portugal (physico-chemical and phytoplankton quality elements). Estuar. Coast Shelf Sci. 67 (3), 382–398. https://doi.org/10.1016/j.ecss.2005.11.029.

Lucas, L.V., Sereno, D.M., Burau, J.R., Schraga, T.S., Lopez, C.B., Stacey, M.T., Parchevsky, K.V., Parchevsky, V.P., 2006. Intradaily variability of water quality in a shallow tidal lagoon: mechanisms and implications. Estuar. Coast 29 (5), 711–730.

Mahanty, M.M., Mohanty, P.K., Pattnaik, A.K., Panda, U.S., Pradhan, S., Samal, R.N., 2016. Hydrodynamics, temperature/salinity variability and residence time in the Chilika lagoon during dry and wet periods: measurement and modelling. Continent. Shelf Res. 125, 28–43. https://doi.org/10.1016/j.csr.2016.06.017.

Malta, E. jan, Stigter, T.Y., Pacheco, A., Dill, A.C., Tavares, D., Santos, R., 2017. Effects of external nutrient sources and extreme weather events on the nutrient budget of a southern European coastal lagoon. Estuar. Coast 1–18. https://doi.org/10.1007/s12237-016-0150-9.

Martinez, E., Antoine, D., D'Ortenzio, F., Montégut, C.B., 2011. Phytoplankton spring and fall blooms in the North Atlantic in the 1980s and 2000s. J. Geoph. Research 116, C11029. https://doi.org/10.1029/2010JC006836, 2011.

Medina-Galván, J., Osuna-Martínez, C.C., Padilla-Arredondo, G., Frías-Espericueta, M.G., Barraza-Guardado, R.H., Arreola-Lizárraga, J.A., 2021. Comparing the biogeochemical functioning of two arid subtropical coastal lagoons: the effect of wastewater discharges. Ecosys. Health Sustain. 7, 1. https://doi.org/10.1080/20964129.2021.1892532.

Meyers, L., Pedro, P., Beltrão, J., Gliesche, C., Dionisio, L., 2010. Anthropogenic effects in a coastal lagoon (South Portugal) related to tidal and spatial changes in nutrients. WSEAS Trans. Environ. Dev. 7 (6), 529–538.

Navarro, G., Ruiz, J., Huertas, I.E., García, C.M., Criado-Aldeanueva, F., Echevarría, F., 2006. Basin-scale structures governing the position of the deep fluorescence maximum in the Gulf of Cádiz. Deep Sea Res. Part II Top. Stud. Oceanogr. 53 (11), 1261–1281. https://doi.org/10.1016/j.dsr2.2006.04.013.

Newton, A., Mudge, S.M., 2003. Temperature and salinity regimes in a shallow, mesotidal lagoon, the Ria Formosa, Portugal. Estuar. Coast Shelf Sci. 57 (1–2), 73–85. https://doi.org/10.1016/S0272-7714(02)00332-3.

Newton, A., Mudge, S.M., 2005. Lagoon-sea exchanges, nutrient dynamics and water quality management of the Ria Formosa (Portugal). Estuar. Coast Shelf Sci. 62 (3), 405–414. https://doi.org/10.1016/j.ecss.2004.09.005.

Newton, A., Icely, J., Cristina, S., Brito, A., Cardoso, A.C., Colijn, F., Riva, S.D., Gertz, F., Hansen, J.W., Holmer, M., Ivanova, K., Leppäkoski, E., Canu, D.M., Mocenni, C., Mudge, S., Murray, N., Pejrup, M., Razinkovas, A., Reizopoulou, S., Pérez-Ruzafa, A., Schernewski, G., Schubert, H., Carr, L., Solidoro, C., Viaroli, P., Zaldívar, J.M., 2014. An overview of ecological status, vulnerability and future perspectives of european large shallow, semi-enclosed coastal systems, lagoons and transitional waters. Estuar. Coast Shelf Sci. 140, 95–122. https://doi.org/10.1016/j.ecss.2013.05.023.

Nieblas, A.E., Sloyan, B.M., Hobday, A.J., Colemanm, R., Richardson, A.J., 2009. Variability of biological production in low wind-forced regional upwelling systems: a case study off southeastern Australia. Limnol. Oceanogr. 54, 1548–1558. https://doi.org/10.4319/lo.2009.54.5.1548.

Niencheski, L.F., Windom, H.L., 1994. Nutrient flux and budget in patos lagoon estuary. Scie. Total Environ. 149, 53–60. https://doi.org/10.1016/0048-9697(94)90004-3.

Nixon, S.W., 1982. Nutrient dynamics, primary production and fisheries yields of lagoons. Oceanol. Acta, nº SP. In: Proceedings International Symposium on Coastal Lagoons SCORE/IABO/UNESCO, Bordeaux, 8-14 September, 1981, pp. 357–371.

Nixon, S.W., 1995. Coastal marine eutrophication: a definition, social causes, and future concerns. Ophelia 41, 199–219. https://doi.org/10.1080/00785236.1995.10422044.

Pacheco, A., Ferreira, Ó., Williams, J.J., Garel, E., Vila-Concejo, A., Dias, J.A., 2010. Hydrodynamics and equilibrium of a multiple-inlet system. Mar. Geol. 274 (1–4), 32–42. https://doi.org/10.1016/j.margeo.2010.03.003.

Pacheco, A., Ferreira, Ó., Williams, J.J., 2011. Long-term morphological impacts of the opening of a new inlet on a multiple inlet system. Earth Surf. Process. Landforms 36, 1726–1735. https://doi.org/10.1002/esp.2193.

Paerl, H.W., Valdes, L.M., Peierls, B.L., Adolf, J.E., Harding, L.W., 2006. Anthropogenic and climatic influences on the eutrophication of large estuarine ecosystems. Limnol. Oceanogr. 51 (1 part 2), 448–462. https://doi.org/10.4319/lo.2006.51.1_part_2.0448.

Peng, H., Jiang, A., Wang, H., 2021. Adsorption and desorption characteristics of phosphorus on sediments in panzhihua section of Jinsha River, China. IOP conf. Series. Earth Environ. Scie. 651, 042059. https://doi.org/10.1088/1755-1315/651/4/042059.

Pereira-Filho, J., Schettini, C.A., Rörig, L.R., Siegle, E., 2001. Intratidal variation and net transport of dissolved inorganic nutrients, POC and chlorophyll a in the Camboriú River Estuary, Brazil. Estuar. Coast Shelf Sci. 53, 249–257. https://doi.org/10.1006/ecss.2001.0782.

Phleger, F.B., 1981. A review of some general features of coastal lagoons. In: Coastal Lagoon Research, Present and Future: Proceedings of a Seminar. United Nations Educational, Scientific, and Cultural Organization, Paris, France, pp. 7–14. UNESCO Technical Papers in Marine Science 33.

Portela, L.I., 2012. Evolução morfológica recente da zona lagunar da Ria Formosa. In: Atas das 2.as Jornadas de Engenharia Hidrográfica, Lisboa, 20-22 de junho de 2012, pp. 291–294 (in Portuguese).

Puppin, A., Roner, M., Finotello, A., Ghinassi, M., Tommasini, L., Marani, M., D'Alpaos, A., 2023. Analysis of organic matter decomposition in the salt marshes of the Venice Lagoon (Italy) using standard litter bags. J. Geophys. Res.: Biogeosciences 128, e2022JG007289. https://doi.org/10.1029/2022JG0072.

Ramírez, J.A., Poillon, M.S., Gómez, M.A.R., de León, D.A.S., 2012. Export of materials along a tidal river channel that links a coastal lagoon to the adjacent sea. Braz. J. Oceanogr. 60 (3), 311–322. https://doi.org/10.1590/S1679-87592012000300004.

Relvas, P., Barton, E.D., 2002. Mesoscale patterns in the cape São Vicente (Iberian Peninsula) upwelling region. J. Geophys. Res. 107 (C10), 3164. https://doi.org/10.1029/2000JC000456 (28 (1–23)).

Rosa, A., Cardeira, S., Pereira, C., Rosa, M., Madureira, M., Rita, F., Jacob, J., Cravo, A., 2019. Temporal variability of the mass exchanges between the main inlet of Ria Formosa lagoon (southwestern Iberia) and the Atlantic Ocean. Estuar. Coast Shelf Sci. 228. https://doi.org/10.1016/j.ecss.2019.106349.

Rosa, A., Cravo, A., Jacob, J., Correia, C., 2022. Water Quality of a southwest Iberian coastal lagoon: spatial and temporal variability. Continent. Shelf Res. 245, 104804. https://doi.org/10.1016/j.csr.2022.104804.

Roselli, L., Cañedo-Argüelles, M., Costa Goela, P., Cristina, S., Rieradevall, M., D'Adamo, R., Newton, A., 2013. Do physiography and hydrology determine the physico-chemical properties and trophic status of coastal lagoons? A comparative approach. Estuar. Coast Shelf Sci. 117, 29–36. https://doi.org/10.1016/j.ecss.2012.09.014.

Ruardij, P., Van Raaphorst, W., 1995. Benthic nutrient regeneration in the ERSEM ecosystem model of the North Sea. NJSR (Neth. J. Sea Res.) 33 (3/4), 453–483. https://doi.org/10.1016/0077-7579(95)90057-8.

Salles, P., 2001. Hydrodynamic Controls on Multiple Tidal Inlet Persistence. Woods Hole Oceanographic Institution, p. 272. PhD Thesis Massachusetts Institute of Technology and.

Salles, P., Voulgaris, G., Aubrey, D., 2005. Contribution of nonlinear mechanisms in the persistence of multiple tidal inlet systems. Estuar. Coast Shelf Sci. 65 (3), 475–491. https://doi.org/10.1016/j.ecss.2005.06.018.

Serpa, D., Falcão, M., Duarte, P., Fonseca, L.C., Vale, C., 2007. Evaluation of ammonium and phosphate release from intertidal and subtidal sediments of a shallow coastal lagoon (Ria Formosa - Portugal): a modelling approach. Biogeochemistry 82, 291–304. https://doi.org/10.1007/s10533-007-9076-4.

Smith, N.P., 1994. Water, salt, and heat balances of coastal lagoons. In: Kjerfve, B. (Ed.), Coastal Lagoon Processes. Elsevier, Amsterdam, The Netherlands, pp. 69–101.

Silva, J.R.A., Leitão, P.C., Braunschweig, F., Neves, R., 2002. Ria Formosa 3D hydrodynamic model. A contribution for the understanding of the Faro-Olhão Inlet processes. Proceedings of Littoral 2002, pp. 197–207 (in Portuguese).

Simons, R.D., Catlett, D., 2023. Regulation of a surface chlorophyll hotspot by wind-driven upwelling and eddy circulation in the Santa Barbara Channel, Southern California. Prog. Oceanogr. 217, 103096. https://doi.org/10.1016/j.pocean.2023.103096.

Simpson, J.H., Vennel, R., Souza, A.J., 2001. The salt fluxes in a tidally-energetic estuary. Estuar. Coast Shelf Sci. 52, 131–142. https://doi.org/10.1006/ecss.2000.0733.

Sontek, 2005. Current Surveyor SystemManual: Software Version 4.30 San Diego, California, p. 160.

Sylaios, G.K., Tsihrintzis, V.A., Akratos, C., Haralambidou, K., 2006. Quantification of water, salt and nutrient exchange processes at the mouth of A mediterranean coastal lagoon. Environ. Monit. Assess. 119, 275–301. https://doi.org/10.1007/s10661-005-9026-3.

Ventura Soares, C., Onofre, J.M., Grade, N., 2001. Caracterização hidrodinâmica do sistema de barras da Ria Formosa. Actas das II Jornadas Portuguesas de Engenharia Costeira e Portuária. Associação Internacional de Navegação, Sines, p. 11 (in Portuguese).

Wilkerson, F.P., Lassiter, A.M., Dugdale, R.C., Marchi, A., Hogue, V.E., 2006. The phytoplankton bloom response to wind events and upwelling nutrients during the

CoOP WEST study. Deep-Sea Res. Part II Top. Stud. Oceanogr. 53, 3023–3048. https://doi.org/10.1016/j.dsr2.2006.07.007.

Winder, M., Cloern, J.E., 2010. The annual cycles of phytoplankton biomass. Phil. Trans. R. Soc. B. 365, 3215–3226. https://doi.org/10.1098/rstb.2010.0125.

Zainol, Z., Akhir, M.F., Samsuri Abdullah, S., 2020. Hydrodynamics, nutrient concentrations, and phytoplankton biomass in a shallow and restricted coastal lagoon under different tidal and monsoonal environmental drivers. Regional Studies in Marine Science 38, 101376. https://doi.org/10.1016/j.rsma.2020.101376.

Zaytsev, O., Cervantes-Duarte, R., 2018. Nutrient flux estimates in a tidal basin: a case study of Magdalena lagoon, Mexican Pacific coast. Estuarine. Coast Shelf Sci 207, 16–29. https://doi.org/10.1016/j.ecss.2018.03.013.

Zhan, P., Krokos, G., Gittings, J.A., Raitsos, D.A., Guo, D., Papagiannopoulos, N., Hoteit, I., 2022. Physical forcing of phytoplankton dynamics in the Al-Wajh lagoon (Red Sea). Limnology and Oceanography Letters 7 (2022), 373–384. https://doi.org/10.1002/lol2.10266.

Zimmerman, J.T.F., 1981. The flushing of well-mixed tidal lagoons and its seasonal fluctuation. In: Lasserre, Postma, H. (Eds.), Coastal Lagoon Research, Present and Future. United Nations Educational, Scientific, and Cultural Organization, Paris, France, pp. 15–26. UNESCO Technical Papers in Marine Science 32.

Zoidou, M., Kokkobs, N., Sylaios, G., 2022. Dynamics of water, salt, and nutrients exchange at the inlets of three coastal lagoons. J. Mar. Sci. Eng. 10 (2), 205. https://doi.org/10.3390/jmse10020205.