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Water quality of a southwest Iberian coastal lagoon: Spatial and temporal variability

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ABSTRACT

The present work aims to characterize Ria Formosa water quality considering its spatial, and temporal variability at two scales: short-term (among seasons) and long-term to evaluate its evolution over the past 40 years, by comparing six historical datasets with data obtained in this study. To attain these goals, four field surveys under different seasons and/or weather conditions were conducted between 2017 and 2019 at seven sites along the Ria Formosa, covering the water bodies specified for this system. *In situ* measurements (temperature, salinity, pH and dissolved oxygen) and water sampling for determination of nutrients, chlorophyll *a* and suspended solids were taken every 2 h at each site, during complete semidiurnal tidal cycles. Moreover, these data were complemented with *in situ* data acquired at a high frequency (every 15 min) by a real time observational station deployed at an inner area, close to a main channel, where the anthropogenic pressure is more intense. Data analysis clearly depict a spatial variability pattern along the Ria Formosa, as well as a temporal heterogeneity, influenced by the contribution of precipitation, sediments, wind and water exchanges with the adjacent ocean. Between sampling sites, the lowest variability of water quality parameters occurred at the boundary coastal station, at the main inlet, in permanent connection with the ocean, while the maximum variability was found at both the lagoon edges, mainly due to the shallowness of the water column. Temporally, the highest concentrations of nutrients were obtained during the Wet/rainy conditions survey, under the influence of runoff. The lowest concentrations of nutrients were attained during the Summer, except for phosphate, due to consumption by phytoplankton. Although the sampling frequency along time has been limited, Ria Formosa water quality data from the last 40 years shows a decreasing trend in nutrients concentration and a marginal increase of dissolved oxygen, suggesting a water quality improvement over time, in contrast with other coastal lagoons that are showing a water quality deterioration due to an increasing anthropogenic pressure. Altogether, these are relevant aspects to consider regarding Ria Formosa present and future management, including climate change and anthropogenic pressures susceptibility assessment and to use them within an international context by comparison with other similar systems.

1. Introduction

Since the 20th century, it has been observed a continuous degradation of coastal systems, including coastal lagoons, through the input of nitrogen and phosphorus (Breitburg et al., 2018), enhanced by orders of magnitude compared to the open ocean (Lønborg et al., 2021). Such nutrients input is mostly linked to agricultural and livestock production intensification, wastewaters discharges, and to the atmosphere by fossil fuel burning (Galloway et al., 2004), accompanied by a removal of ecosystem filtering and buffering capacity (e.g., wetland loss; Verhoeven et al., 2006). Considering the rising concern about the importance of coastal lagoon ecosystems in the 1950's (e.g., Kjerfve, 1994; Nixon, 1995) to protect, preserve and even restore these environments has become a major issue (Erostate et al., 2022). Coastal lagoons are transitional and highly productive systems, whose characteristics and dynamics depend critically on the interplay between the terrestrial inputs, the atmosphere (e.g. balance between precipitation and evaporation, and surface heat balance) and the exchanges with the ocean, including upwelling events (Kjerfve, 1994; Barbosa, 2010; Cervantes-Duarte et al., 2013). Therefore, the water quality is regulated by mixing, circulation

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patterns and residence time of the water masses that control the dispersion of organic matter, nutrients and gases and ultimately the biological communities and the ecosystem services (Best et al., 2007; Brito et al., 2012a). Moreover, coastal lagoons are sensitive systems responding quickly to environmental changes associated to anthropogenic pressure and climate changes, which can impact the services provided by these ecosystems. Hence, these environments are extremely vulnerable to eutrophication, deoxygenation, acidification, among other problems, as found in many coastal systems (Erostate et al., 2022; Hagens et al., 2015; Romero-Sierra et al., 2018). This fact drives the need for observation to understand the water quality variability to effectively support (short and long-term) management of these important systems. In this context, many studies have been conducted worldwide to assess water quality and evaluate the impact of changing environmental conditions. There are several lagoons and coastal systems in Europe – Mediterranean, such as Mar Menor (Pérez-Ruzafa et al., 2019, 2020), Venice lagoon (Çevirgen et al., 2020), Remolar and Ricarda coastal lagoons (Cañedo-Argüelles et al., 2012), Northwestern Mediterranean coastal waters (Temino-Boes et al., 2021) including Thau Lagoon (Derolez et al., 2020) –, or elsewhere, such as in Mexico (Mexican Caribbean lagoon (Romero-Sierra et al., 2018); Términos Laggon (Cuevas et al., 2021)) and Brazil (Patos Laggon; Seiler et al., 2020) under distinct anthropogenic pressure. However, their vulnerabilities depend on their specific characteristics, such as the nutrients amounts entering these systems, hydrodynamic regimes and tidal influence that controls the water residence time, and weather conditions including those associated to climate changes. There are many cases in literature stating the deterioration of the water quality of coastal lagoons (e.g., Romero-Sierra et al., 2018; Çevirgen et al., 2020; Seiler et al., 2020), while there are some systems that are recovering, like in some areas found around the Mediterranean. This is the case of Mar Menor coastal lagoon due to reduction of nitrate discharges (of about 82%; Pérez-Ruzafa et al., 2019), as well as Northern Mediterranean coastal waters (including Thau Laggon), due to reduction in precipitation and nutrients availability (Derolez et al., 2020; Temino-Boes et al., 2021).

The Ria Formosa, located on the southwest coast of Iberia, is considered one of the most important and productive coastal systems of Portugal (Fig. 1) due to its key socioeconomic, ecological and environmental role. The water quality in this ecosystem is closely dependent on tidal exchanges with the ocean (e.g. Cravo et al., 2014; Rosa et al., 2019) and also on the human pressure (Newton et al., 2014). Like many other European coastal lagoons, it represents an attractive and popular environment where urban and tourism pressure is evident, particularly during the Summer (Newton et al., 2014).

So far, Ria Formosa water quality characterization has been mostly accomplished by discrete and discontinuous sampling over time and space, rendering difficult temporal and spatial patterns assessment of this system as a whole. Most of these studies were carried out mainly after the 1970's, particularly during the 1980's to 1990's (e.g., Lima and Vale, 1980; Cunha and Massapina, 1984; Benoliel, 1984, 1985, 1989; Falcão et al., 1985; Brockel, 1990; Cortez, 1992; Thiele-Gliesche, 1992; Newton, 1995; Falcão, 1997), when several studies reported water quality deterioration by intensification of anthropogenic pressure. However, after 2000's more studies have been performed within the scope of the Water Framework Directive (WFD) implementation, despite not following a regular temporal coverage, and being mainly focused on the western sector of the lagoon (Ferreira et al., 2005, 2006; Loureiro et al., 2005; Pereira et al., 2009; Brito et al., 2009, 2010, 2012a; Goela et al., 2009; Newton et al., 2010) and in areas close to wastewater treatment plants (WWTP; Cravo et al., 2015). Some of these studies have

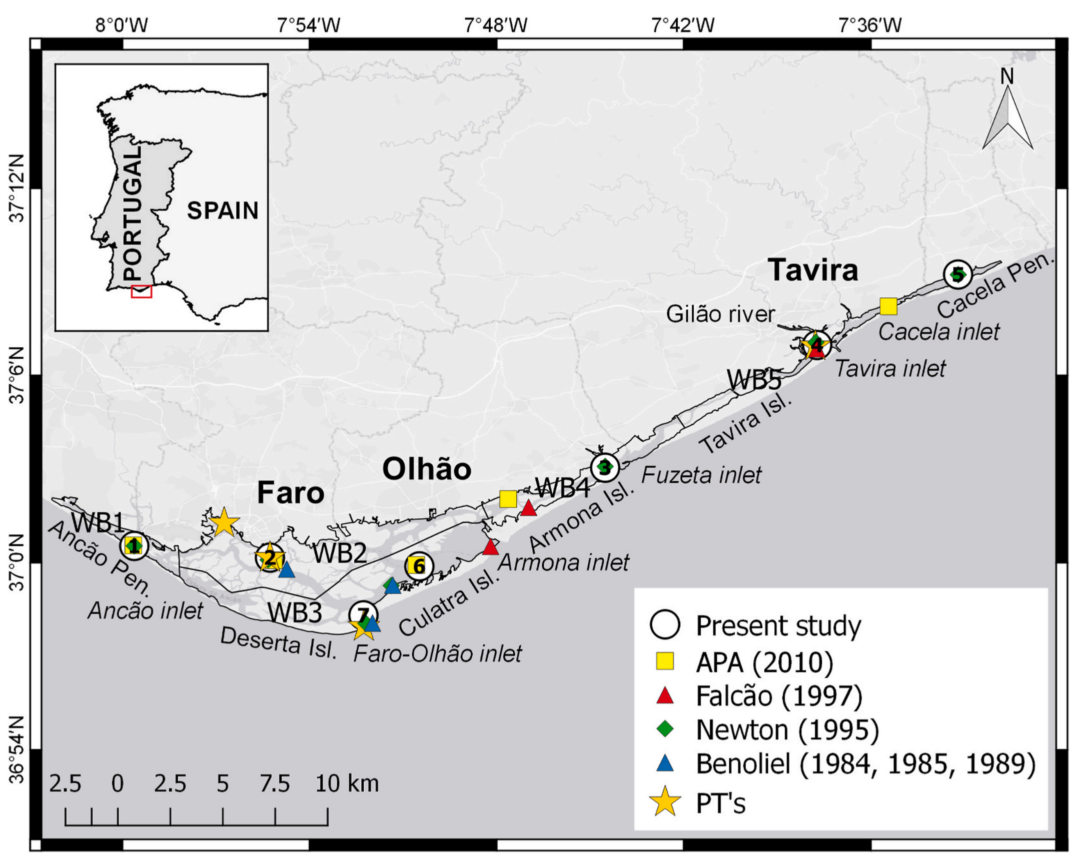

Fig. 1. Location and representation of Ria Formosa, on the south coast of Portugal, including the limits of the water bodies (WB, black contours), the pressure transducers (PTs) deployed (orange stars) and the sampling stations (white circles with numbers), including those from historical datasets: 2010 dataset (APA – Agência Portuguesa do Ambiente, 2010; yellow squares); 1987/1989 dataset (Newton, 1995; green diamonds); 1985/1986 dataset (Falcão, 1997; red triangles); 1980/1984 datasets (Benoliel, 1984, 1985, 1989; blue triangles).

reported that the water quality was increasing due to alterations of human activities along with hydrodynamical changes. Consistent monitoring programs covering several stations along the extent of the lagoon are almost inexistent, except for one led from 1985 to 2009 reported in Valença et al. (2011). In 2010, APA (Agência Portuguesa do Ambiente; https://snirh.apambiente.pt/) implemented a national monitoring program to classify the ecological status of the Portuguese water bodies ("Avaliação do Estado Ecológico das Massas de Águas" - EEMA), which characterized the Ria Formosa during one day only, in March, at both low and high water. Since then, except for some studies focused on the mass exchanges at the main inlets (Cravo et al., 2014, 2019; Malta et al., 2016; Rosa et al., 2019), works dedicated to the evaluation of the current state of the water quality of the Ria Formosa, over the different water bodies, are scarce. Therefore, to fulfil this gap of knowledge, an updated spatial and temporal characterization of the water quality along the Ria Formosa is fundamental. To attain this goal, four field surveys were performed synoptically at several stations along the entire extent of Ria Formosa comprehending all the water bodies defined for this coastal lagoon (Ferreira et al., 2005, 2006). A real time observation station (RTO), comprising a fixed multiparametric probe, was also deployed for almost three years in the water body where the anthropogenic pressure is more intense, allowing to characterize according to different time scales, including episodic events not captured by discrete sampling. In addition, six historical datasets were compared with data obtained in the present study, to analyze the temporal evolution of the water quality parameters over the last 40 years. Within this scope, this work aims to: a) characterize the spatial variability of the water quality within Ria Formosa, based on the data obtained at seven sampling sites and on the application of trophic and chlorophyll *a* indexes; b) characterize the temporal water quality variability based on data from the field surveys conducted in different weather/seasonal conditions, complemented by the RTO data; and c) assess the temporal evolution of the water quality parameters over the past 40 years, by comparison with historical datasets and contextualize it in relation to other coastal lagoons worldwide.

2. Study area

The Ria Formosa is a multi-inlet barrier system, on the south coast of Portugal, that extends along 55 km and has a maximum width of 6 km, covering about 100 km^2. The intertidal area (*ca.* 55 km^2) is mainly formed by sand, muddy sand flats, and saltmarsh (Rodrigues et al., 2021). The tidal flats and saltmarshes represent more than two thirds of the total lagoon area (Carrasco et al., 2021). The saltmarshes comprise silt and fine sand (Bettencourt, 1994), while coarser (sand to shingle) shell-rich sediment of marine provenance is found on tidal channels and on the lower domain of intertidal flats (Andrade et al., 2004). It is delimited by 5 barrier islands, 2 peninsulas and 6 inlets (Fig. 1). Two of the inlets were artificially opened and stabilized (Faro-Olhão and Tavira inlets), three were artificially relocated (Ancão, Fuzeta and Cacela inlets) and the remaining is a natural inlet (Armona) (Fig. 1). The inlets are connected by a complex network of natural and partially dredged channels, which allows the recirculation of water within the lagoon and permanent exchange with the Atlantic Ocean (Matias et al., 2008; Alcântara et al., 2012).

This coastal lagoon is under the influence of semidiurnal tides in a mesotidal regime (range from 1.5 to 3.5 m) felt all over the lagoon (Jacob and Cravo, 2019), which represents the main driver for water circulation inside the system (Salles et al., 2005). The mean depth is 3.5 m, and can range from 6 to 13 m in the main channels and inlets (Falcão and Vale, 1990; Barbosa, 2010; Cravo et al., 2014). This basin is mostly influenced by five small rivers and streams, most of them temporary/totally dry during Summer. Gilão River located in Tavira (Fig. 1) is the permanent riverine source in the lagoon, with a mean flow rate of 192 m^3 day^{-1} (Falcão et al., 2003), but can reach values close to 0 during Summer (see Cravo et al., 2020). Besides the freshwater input from natural sources, there is also about 2.5 $\times$ 10^4 m^3 daily input of WWTP effluent discharges into this system (Cravo et al., 2015), about 3–4 orders of magnitude lower than the total tidal prism (exchange of water with the coastal ocean along a semidiurnal tidal cycle, ranging from 50 $\times$ 10^6 m^3 in neap tide to 180 $\times$ 10^6 m^3 in spring tide; unpublished data, as reported in Rosa et al., 2019). In this coastal lagoon, between 50 and 75% of the water is renewed in each tidal cycle (Tett et al., 2003). The latter leads to low residence times at the main inlets (0.5–2 days; Tett et al., 2003; Saraiva et al., 2007), but increases at the innermost areas (7–18 days; Fabião et al., 2016). The difference of prism between spring and neap tides leads to disparities in currents velocities and, consequently, affects the residence time inside the lagoon (Dias and Sousa, 2009).

In the south coast of Portugal, the climate is temperate, the annual mean rainfall is low (*ca.* 490 mm.year^{-1}; IPMA - Portuguese Institute for Sea and Atmosphere; http://www.ipma.pt/) and rainfall at Faro (nearby Ria Formosa) has been decreasing over the last 30 years, along with a slight increase in atmospheric temperature (see Figure SM 1 A and B in the Supplementary Material). Due to the low freshwater input and the tidal exchanges in this lagoon, the water column is well mixed vertically and salinity is similar to the adjacent coast, around 36 (Cravo et al., 2014, 2019; Rosa et al., 2019).

Five water bodies (WB) have been defined in the lagoon under the scope of WFD, as identified by black contours in Fig. 1, affected by different circulation patterns and human pressures, presenting distinct water characteristics (Ferreira et al., 2005, 2006). The water bodies division is apparently artificial, since there are no physical boundaries between them (Cravo et al., 2020). WB1 covers the western part of the lagoon, WB2 represents the innermost area, which is highly influenced by anthropogenic pressure from the main cities (Faro and Olhão), WB3 represents the outermost area of the lagoon, which comprises two main channels (Faro and Olhão) and three inlets (Faro-Olhão, Armona and Ancão), WB4 represents an area with lower human pressure, and lastly WB5 covers the area influenced by the permanent freshwater source located in Tavira and also the eastern part of the lagoon. In terms of hydrodynamics, this coastal lagoon can be divided into three different sectors: a western sector, which comprises Ancão, Faro-Olhão and Armona inlets; a central sector, including the Fuzeta and Tavira inlets; and an eastern sector, served by Cacela inlet (Salles et al., 2005). The western sector is the most important sector of Ria Formosa regarding water exchanges, since it is responsible for 90% of the water volume exchanged with the coastal ocean in each tidal cycle (Salles et al., 2005; Pacheco et al., 2010). Given the strong interconnectivity between Ria Formosa and the Atlantic Ocean, oceanographic processes that prevailed in the coastal ocean, including upwelling and coastal countercurrent events, strongly influence water quality and phytoplankton dynamics inside the lagoon (Rosa et al., 2019). The offshore wave climate is dominated by W-SW waves (71%) of the total incoming waves (Costa et al., 2001) and has no major propagation inside the lagoon (Carrasco et al., 2018).

3. Material and methods

To attain the main objectives of this study, data from four conventional field surveys conducted under distinct weather/seasonal conditions at seven sampling locations representative of the Ria Formosa five water bodies (Fig. 1) were complemented by data from a deployed RTO station (located at station 2; Fig. 1), as described below.

3.1. Field surveys

Four field surveys were conducted to characterize the variability of the water quality along different weather conditions, expectedly to correspond to different seasons. Three field surveys were carried out in Spring, Summer and Autumn of 2017 (30 and 31 May to follow the concurrent conditions when the RTO was deployed; 14 and 15

September, end of Summer, usually when the water temperature is maximum; 25 and 26 October, respectively), synoptically along 7 stations to comprise the five water bodies established for the Ria Formosa. Five stations were located at inner areas in the main channels: station 1 – representative of WB1; station 2 – representative of WB2; station 3 – representative of WB4; station 4 – representative of the area influenced by the permanent freshwater source, identified as WB5-R; station 5 – representative of WB5. The most external areas were represented by station 6 at WB3 and station 7 at the main inlet - Faro-Olhão inlet (Boundary Station, BS; Fig. 1). The BS station was used to characterize the adjacent oceanic conditions. As it did not rain in appreciable amounts during Winter 2018, the fourth field survey was carried out only in 2019 (9 and 10 April) after 4 days of rain to evaluate the rainfall influence on the water quality, representative of a distinct weather/season conditions, most common during the Winter season. This campaign was identified as the Wet conditions survey in the temporal data analysis. In this field survey, only four sites, those considered mostly different, were considered (BS – the boundary station, WB1 and WB5 – representative of the lagoon edges, and WB5-R – the only station with contribution from Gilão river).

In situ measurements and water samples were taken every 2 h during a complete semidiurnal tidal cycle (~12.5 h) at each site, during intermediate tides (Table 1). In the last field survey, at BS, only low-tide and high-tide peaks were sampled. *In situ* measurements of water temperature, salinity, pH and dissolved oxygen (concentration in mg/L and saturation percentage) were conducted using four YSI multiparameter probes (EXO2, YSI 6820, YSI XL 660 and YSI ProDSS), with similar sensors specifications (for range, accuracy and resolution of EXO2 sensors, see Table 1 in Cravo et al., 2020). EXO2 and YSI 6820 multiparametric probes included optical sensors to measure dissolved oxygen, while YSI XL 660 and YSI ProDSS included membrane polarographic ones, with the sensor of YSI XL 660 having an accuracy slightly lower (±0.2 mg/L for 0–20 mg/L) than the three other sensors (±0.1 mg/L for 0–20 mg/L). Dissolved oxygen sensors were air calibrated under humid conditions before the measurements, as required by the manufacturer, and measurements were checked along the day using the Winkler method (Winkler, 1888). Before the field surveys, conductivity, and pH sensors of all the multiparameter probes were calibrated using specific calibration solutions (50 mS/cm for conductivity and pH 7 and 10). Water samples were collected using 5 L Niskin bottles at water columns with depths >2 m or using sampling cups at surface levels (first 20 cm) for determination of nutrients (ammonium, nitrate, nitrite, phosphate and silicate), chlorophyll *a* and suspended solids concentrations. Sea surface elevation was also measured every 10 min by four pressure transducers (PTs; two Level TROLL, one Infinity and one DIVER) located in different locations. Two PTs were at innermost areas near Faro city, one was in Faro-Olhão inlet and the other near Tavira inlet (orange stars in Fig. 1).

3.2. Laboratorial analysis

The water samples were filtered with specific filters for suspended solids (0.45 μm pore size, Gelman membrane filters) and chlorophyll *a* (0.7 μm pore size, GF/F Whatman glass fiber filters) determination. The filtered samples were used to determine the nutrients concentration by spectrophotometric methods as described in Grasshoff et al. (1983), based on calibration curves (with $r^2 > 0.99$). Marine Nutrient Standards Kit (OSIL) were used as reference, to guarantee accuracy. To determine the concentration of chlorophyll *a*, the glass fiber filters were frozen at −20 °C until further analysis, and then analyzed using the spectrophotometric method described by Lorenzen (1967). The detection limits were 0.07 μM for nitrate, 0.02 μM for nitrite, 0.09 μM for ammonium, 0.03 μM for phosphate, 0.05 μM for silicate and 0.3 μg/L for chlorophyll *a*. A gravimetric method was used to determine the total suspended solids, as described in APHA (2002).

3.3. Real time observation station (RTO)

RTO data acquired during the analyzed period were used to support the four field surveys data. The RTO probe recorded was deployed close to the main city of Faro, at a fixed station in WB2 on the western sector of Ria Formosa, close to where the field campaign was conducted, to be representative of the water quality of one of the inner main channels (see station 2 in Fig. 1). It was equipped with a multiparameter probe YSI EXO 2, with sensors to measure water temperature, conductivity/salinity, pH, dissolved oxygen (concentration in mg/L and saturation percentage), chlorophyll *a* and turbidity. The multiparameter probe was also equipped with a copper-alloy sensor guard and an anti-fouling wiper to reduce the biofouling in the sensors. Data was measured continuously at the monitoring station with a sampling interval of 15 min. Sensors specifications and maintenance procedures were established and implemented to guarantee the continuous acquisition of the data, the safety of the multiparameter probe and the quality of the data, as described in Cravo et al. (2020).

3.4. Analysis of historical datasets

To evaluate the variability of the water quality over the past 40 years, six historical datasets were compared with the data obtained in this study. The datasets were selected considering common characteristics with the present work, such as sampling stations within the same water bodies and nearest stations (Fig. 1) and same variables (dissolved oxygen, nutrients and chlorophyll *a*), as depicted in Table SM 1 (Supplementary Material section). Three of these studies were conducted between 1980 and 1984 (Benoliel, 1984, 1985, 1989), which included monthly surveys encompassing three stations located in the lagoon (blue triangles in Fig. 1). Other study was performed during 1985–1986 at several stations along the inner area of the lagoon and some inlets (red triangles in Fig. 1), with twice a month sampling, during spring and neap tides, at low and high tide (Falcão, 1997). Another study reports

Table 1
Mean values (range) of air temperature (°C), wind speed (m/s) and precipitation (mm) measured at Faro Airport or Olhão Meteorological Stations (*) (http://www.ipma.pt/) and the tidal range predicted by the Instituto Hidrográfico (Faro-Olhão station; http://www.hidrografico.pt/) for Spring, Summer, Autumn and Wet conditions survey days. For Wet conditions survey, the variation between four days before the survey period (5–8 April) is also presented.

Field campaign/Season	Days	Air temperature (°C)	Wind speed (m/s)	Precipitation (mm)	Tidal range (m)
Spring	30 May	22.2 (17.7–25.4)*	2.6 (0–5.3)*	0*	0.9–3.2
	31 May	23.5 (19.6–26.3)*	1.9 (0–4.5)*	0*	1.1–2.9
Summer	14 September	22.9 (17.4–28.8)	3.1 (0.4–5.5)	0	1.2–2.8
	15 September	21.1 (16.4–26.0)	5.8 (2.8–9.8)	0	1.1–2.9
Autumn	25 October	20.2 (17.9–22.8)	4.2 (2.0–7.2)	0	1.2–2.7
	26 October	21.7 (18.4–26.0)	3.9 (0.6–7.0)	0	1.3–2.7
Wet conditions	5–8 April	13.9 (8.9–18.0)	6.3 (1.6–13.2)	23	–
	9 April	15.0 (11.7–18.7)	5.1 (1.6–10.1)	0	0.8–3.1
	10 April	14.5 (10.5–19.5)	4.2 (0.6–7.9)	0	0.9–3.0

monthly surveys from 1987 to 1989, at several stations covering the entire lagoon with sampling conducted during several tidal conditions (Newton, 1995; green diamonds in Fig. 1). The last field survey considered was performed in March 2010, within the scope of the EEMA project, with samples collected at several stations covering the entire lagoon, at low and high water, at surface and bottom levels (APA – Agência Portuguesa do Ambiente, 2010; yellow squares in Fig. 1). To analyze the temporal evolution of the water quality parameters, boxplots are presented and analyzed in the Discussion section. The confidence level for the assessment of the water quality was also applied to the present and historical datasets (Table SM 2 of Supplementary Material) based on the Baltic Marine Environment Protection Commission (Helsinki Commission). The following temporal coverage criteria were used: i) high confidence level, if data are available in all months of the season; ii) intermediate confidence, if data from one of the months of the season are missing; iii) low confidence when observations are missing in more than one month of the season (from HELCOM, 2019).

3.5. Environmental and oceanographic data settings

The meteorological conditions (precipitation, air temperature, direction and intensity of the wind) that prevailed before or during the field surveys period were provided by IPMA from the Faro airport or Olhão meteorological stations (apart *ca.* 15 km) and are summarized in Table 1. To analyze the large-scale variability of the wind, data were filtered with a Butterworth low-pass filter to remove the high frequency signal. OceanColor Nasa site (https://oceandata.sci.gsfc.nasa.gov/) was also accessed to analyze Sea Surface Temperature (SST) data and chlorophyll *a* concentration from the MODIS-Aqua satellite, from eight-day composite images with a spatial resolution of 4 km.

3.6. Water quality indexes

Two indicators were used to assess the water quality in Ria Formosa water bodies, one accounting for trophic status and the other for chlorophyll *a* status. The trophic index TRIX (Vollenweider et al., 1998) the information of four key water quality parameters: Chla (μg/L); absolute deviation of the dissolved oxygen saturation (% DO); dissolved inorganic nitrogen (DIN: sum of the three inorganic nitrogen forms, i.e. ammonium + nitrate + nitrite; μg/L) and the soluble reactive phosphorus (SRP; μg/L), as expressed in the following equation:

$$\text{TRIX} = [\text{LOG}(\text{Chla} \times |100 - \%\ \text{DO}| \times \text{DIN} \times \text{SRP}) - (-1.5)] / 1.2$$

The TRIX results allow to analyze the trophic conditions of each water body, with the following water quality classification: High [0–4[, Good [4–5[, Moderate [5–6[and Poor [6–10]. This index was applied to the data relative to the four seasonal field surveys conducted in this study, as well as to the historical datasets.

In order to assess the chlorophyll *a* status in Ria Formosa, the benchmarks defined by Brito et al. (2012b) were used in the present study. These authors aimed to assess the ecological quality of the Portuguese coastal waters, using the chlorophyll *a* concentration as a proxy for the phytoplankton biomass. In Table 2 is presented the reference conditions and boundary concentrations proposed by Brito et al. (2012b). To assess the chlorophyll *a* status, the 90th percentile of the chlorophyll *a* concentration was used and compared against the reference condition and boundary concentrations, which has been applied within the scope of the WFD in Europe (Brito et al., 2012b).

Table 2
Chlorophyll *a* reference conditions and boundary concentrations proposed by Brito et al. (2012b) for the adjacent coastal waters (CW) and for the southern coastal lagoons (CW-Ls), based on the 90th percentile.

	Chlorophyll *a* (μg/L)
Reference condition in adjacent CWs	4
Reference condition in southern CW-Ls	5.5
High/Good Boundary in southern CW-Ls	8
Good/Moderate Boundary in southern CW-Ls	12

Two additional water quality indexes were also used to assess the water masses classification of the lagoon along the different periods, considering the WFD, as described in APA – Agência Portuguesa do Ambiente (2021). For chlorophyll *a*, the Ecological Quality Ratio (EQR) was calculated by dividing the reference condition value (5.3 μg/L) for Ria Formosa, considered an open coastal lagoon (type A4), by 90th percentile of chlorophyll *a* concentration during the growing season (between February and October). The classification scale is "High/-Good" (0.67), "Good/Moderate" (0.44), "Moderate/Bad" (0.3), and "Bad/Poor" (0.2). The water masses classification for nutrients was also assessed according to the RIM ratio methodology. For Ria Formosa, considered an open coastal lagoon with salinity >30 PSU (giving the typical oceanic values of salinity in this lagoon), this ratio is calculated by dividing the 90th percentile of nutrient concentrations (ammonium, the sum of nitrate and nitrite, and phosphate) by the reference condition value for open coastal lagoons (type A4; 0.6 mg/L N for nitrate + nitrite; 0.4 mg/L N for ammonium; and 0.06 mg/L P for phosphate). The classification scale is "High" [0, 1[, "Good" [1,2[, and "Moderate" ≥ 2. The mean concentrations referred by the European Environment Agency (EEA) for the European seas in 2013–2017 (EEA – European Environment Agency, 2021) for DIN in winter and Total Phosphorous (TP) as annual mean were also considered to frame and classify the results from this study.

3.7. Statistical analyses

ANOVA test (one-way) for the variables with normal distribution was applied to verify if significant differences existed between the different water bodies and between the four seasons of the year, using a confidence level of 95%, followed by post-hoc Tukey test. Equivalently, Kruskal-Wallis test was used for the variables with non-normal distribution. To demonstrate representative data illustrative of spatial and seasonal trends, boxplots were selected for the average, with the 1st and 3rd quartiles (25% and 75% percentiles, respectively), plotted in R-studio. A Principal Component Analysis (PCA) with standardized data was also performed, aiming to understand and identify the main factors and/or processes that better explain the data variability, as well as the relationship between the variables from the four field surveys.

4. Results

Field data from four field surveys taken along complete tidal cycles encompassing the five waterbodies defined in Ria Formosa are presented along with the complementary data acquired during the same period by the RTO station in WB2. In the subsequent sections, it is described the variability of the water quality and, ultimately, the classification of the water bodies based on water quality indexes.

4.1. Field surveys

4.1.1. Tidal variability of the water quality parameters at the sampled sites

Considering the four field surveys, there was not an evident tidal variability of the water characteristics at any of the seven sampling sites, except for nutrients that clearly varied in antiphase with the sea surface elevation. The sea surface elevation measured at the four deployed PT's (Fig. 1) showed that there is a relatively small tidal distortion at the inner areas where the PT's were deployed, with a phase delay of 30–40 min (not shown). Nutrients presented the highest values during the ebb period and the lowest values during the flood period. The tidal variability of silicate concentration during the Autumn season is exemplified in Fig. 2A. However, during Summer, nitrate variability at the station adjacent to the ocean (BS) showed an opposite behavior, depicting the highest values during the flood period (Fig. 2B).

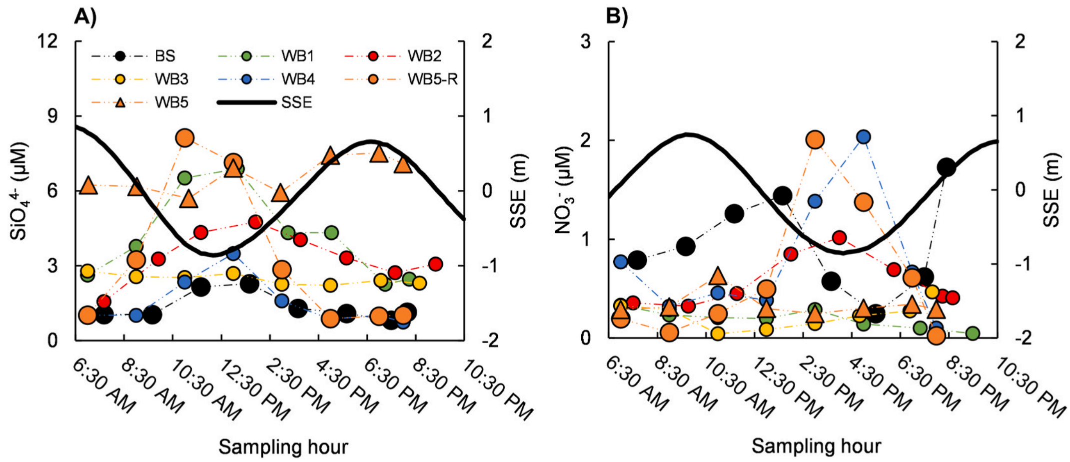

Fig. 2. – Variability of silicate (A) and nitrate (B) concentrations in each WB along the semidiurnal tidal cycles conducted during Autumn and Summer seasons, respectively; the solid curve represents the sea surface elevation due to the tide (SSE, right-hand axis) measured at Faro-Olhão inlet (see Fig. 1).

4.1.2. Spatial variability of the water quality parameters at the sampled water bodies

The average, 25% and 75% percentiles and extreme values of water temperature, salinity, dissolved oxygen, pH, nutrients, chlorophyll *a* and total suspended solids obtained during the four seasonal field surveys at the selected sampling sites characteristic of each of the water bodies

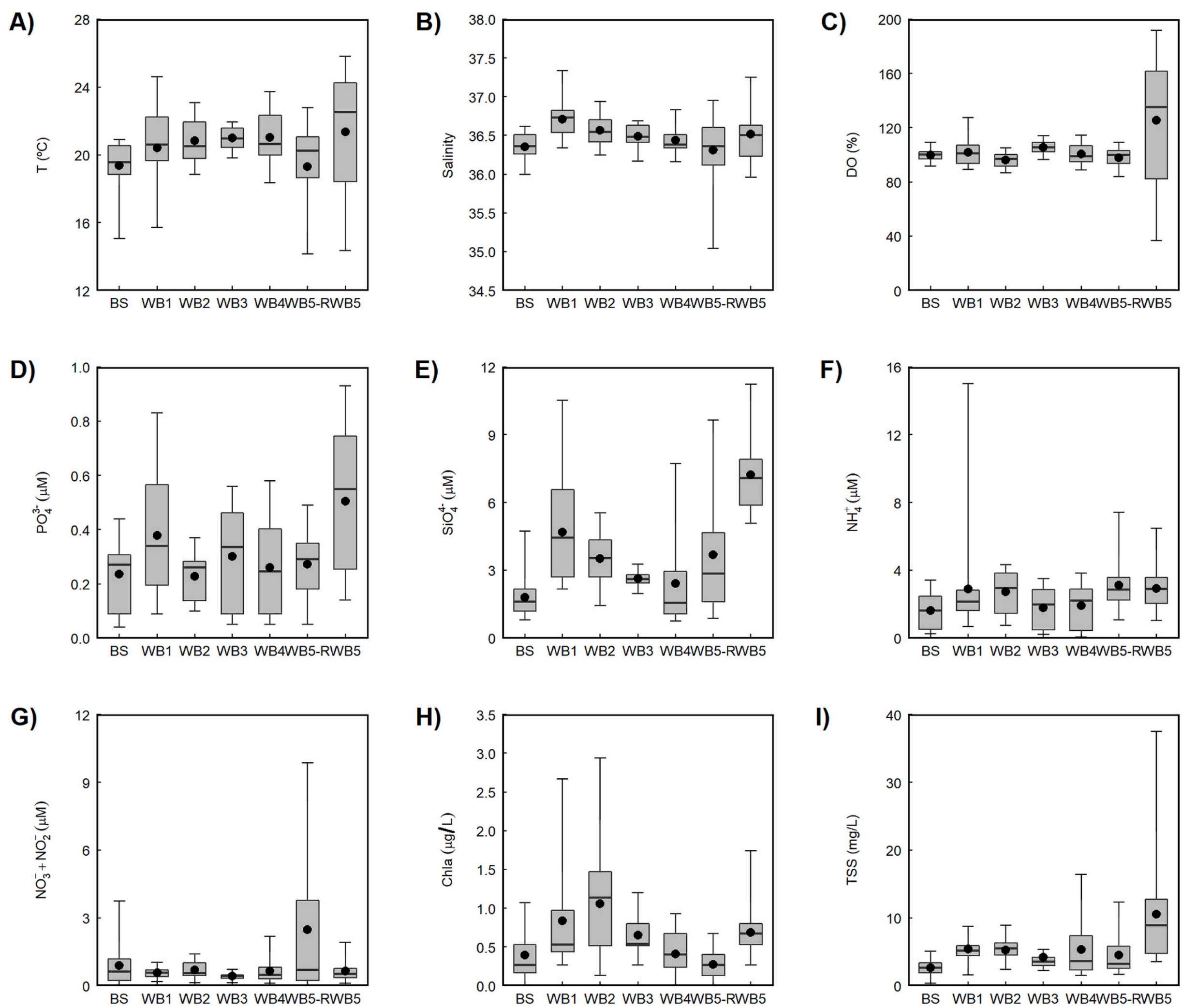

Fig. 3. – Boxplot of water temperature (A), salinity (B), dissolved oxygen (C), phosphate (D), silicate (E), ammonium (F), nitrate + nitrite (G), chlorophyll a (H) and total suspended solids (I) for each water body (WB). In the boxplots, the solid line represents the median, the black dots represent the average, the lower and upper hinges are the 25% and 75% percentiles and whiskers represent the minimum and maximum values.

identified in Ria Formosa are shown in Fig. 3.

Spatially, there were significant differences between sampling sites, for each analyzed parameter. Average water temperature (Fig. 3A) was significantly higher ($p \leq 0.05$) at WB5 (21.3 °C) than at BS (19.4 °C) and WB5-R (19.3 °C). Salinity (Fig. 3B) was typical of coastal waters (>36) and significantly higher ($p \leq 0.05$) at WB1, at the western edge (average 36.7) than at BS, WB4 (average 36.3) and WB5-R (average 36.3) and WB2 (average 36.6). Values of pH (not shown) varied within a narrow range, with the highest variation at WB5 (range 7.6–8.6). Values were similar ($p > 0.05$) between sites, except between WB3 that was higher than WB4 ($p \leq 0.05$). Dissolved oxygen saturation values (Fig. 3C) were high and similar between the different water bodies and BS (average ~ 100%), except at WB5, where the extreme variability was recorded (average 126%; range 37–192%; $p \leq 0.05$).

Nutrients (Fig. 3D–G) presented higher concentrations at the stations located at both the edges of the lagoon than at the remaining water bodies ($p \leq 0.05$), except for nitrate + nitrite. In particular, the average concentration of phosphate was significantly higher ($p \leq 0.05$) at WB5 (0.5 μM) and WB1 (0.4 μM) than at BS and WB2. The average silicate concentration at WB5 (7.2 μM) was significantly higher than at the remaining water bodies, while the average value at WB1 (4.7 μM) was also significantly higher than at BS, WB3 and WB4. Average values at WB2 (3.5 μM) and WB5-R (3.7 μM) were significantly higher than at BS (1.8 μM). Average ammonium concentrations at WB1 (2.9 μM), WB5 (2.9 μM) and WB5-R (3.1 μM) were significantly higher ($p \leq 0.05$) than at BS. Average ammonium concentration at WB3 was significantly lower than the corresponding value at WB5-R. Nitrate + nitrite was significantly higher at WB5-R (average 2.5 μM, range n.d-9.9 μM; $p \leq 0.05$) than the ones found in the remaining sites. Nitrogen was the limiting element (N:P ratio <16; not shown) at all water bodies, except for WB5-R, due to an increase of nitrate concentration. The same was found regarding N:Si ratio (<1) except at BS and WB5-R, where silicon was the limiting element (N:Si ratio >1; not shown).

Average chlorophyll *a* concentration (Fig. 3H) recorded at WB2 (1.1 μg/L) and WB1 (0.8 μg/L) were similar ($p > 0.05$), but significantly higher than at the remaining water bodies, including BS (0.4 μg/L). Total suspended solids (Fig. 3I), like dissolved oxygen, were significant higher at WB5 (average 10.6 mg/L, range 3.5–37.5 mg/L) when compared with the remaining stations ($p \leq 0.05$).

4.1.3. Short-term temporal variability of the water quality parameters at the sampled water bodies

Average, 25% and 75% percentiles and extreme values of water temperature, salinity, dissolved oxygen, nutrients, chlorophyll *a* and total suspended solids concentrations for each temporal survey conducted in different seasonal/meteorological conditions covering the

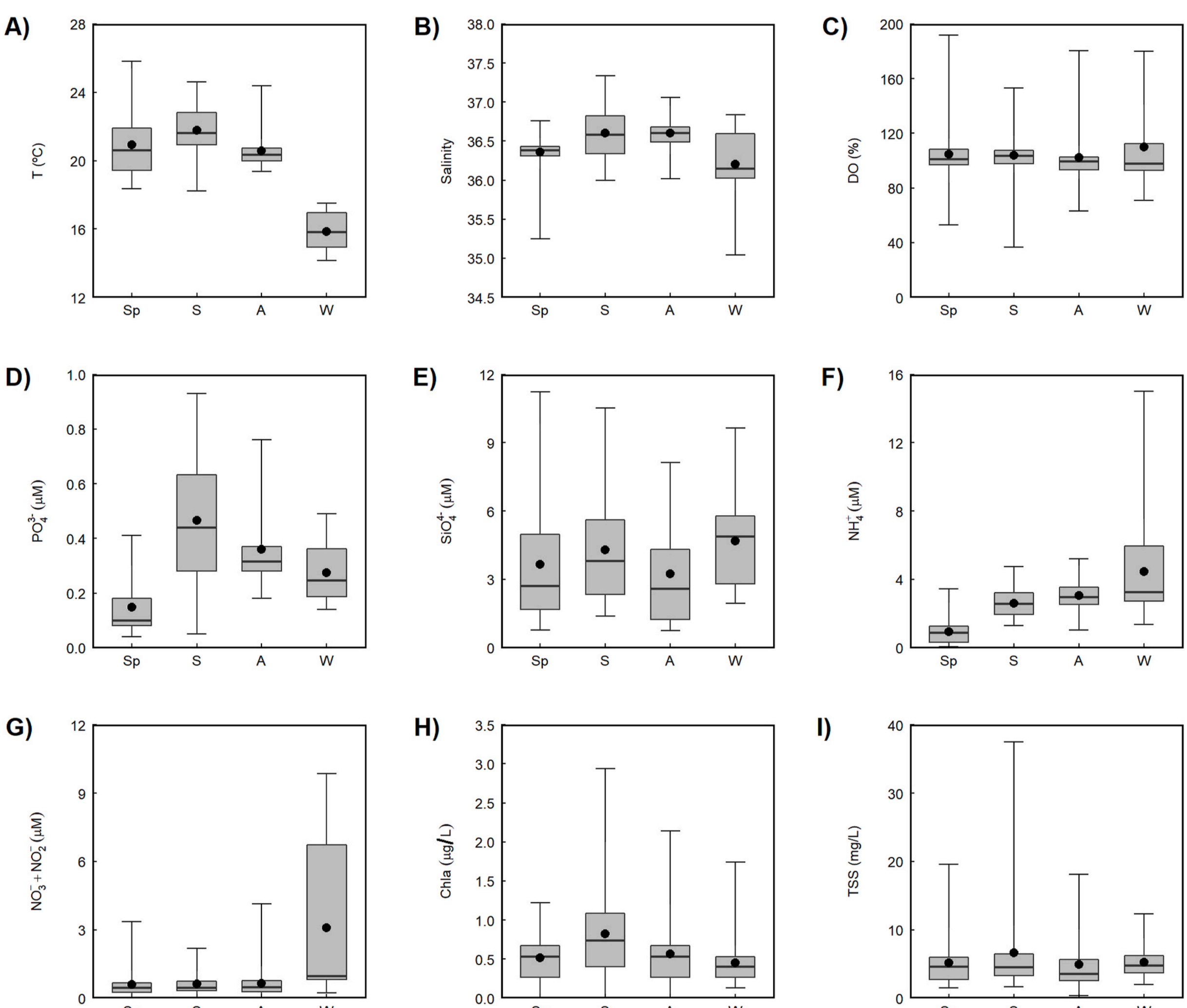

Fig. 4. – Boxplot of water temperature (A), salinity (B), dissolved oxygen (C), phosphate (D), silicate (E), ammonium (F), nitrate + nitrite (G), chlorophyll a (H) and total suspended solids (I) during the different seasonal field surveys (Sp: Spring; S: Summer; A: Autumn; W: Wet conditions). In the boxplots, the solid line represents the median, the black dots represent the average, the lower and upper hinges are the 25% and 75% percentiles and whiskers represent the minimum and maximum values.

seven sampling sites of the Ria Formosa are shown in Fig. 4. Dissolved oxygen (average *ca.* 100%, range 37–192%), silicate (average 3.2–4.7 μM, range 0.7–11.2 μM) and total suspended solids concentrations (average 5.0–6.7 mg/L, ranges 0.4–37.5 mg/L) showed no seasonal differences ($p > 0.05$). Water temperature followed the typical seasonal cycle, significantly higher during Summer (21.8 °C) than during Wet conditions (15.8 °C; $p \leq 0.05$). Spring and Autumn surveys presented similar water temperature ($p > 0.05$). Salinity was significantly lower during Wet conditions and Spring surveys ($p \leq 0.05$), than during Summer and Autumn surveys; the latter two presented similar salinity ($p > 0.05$). pH variability was small, as typical of coastal waters, with most values ranging between 7.8 and 8.3, with no differences between seasonal surveys (not shown). Average phosphate concentration was minimum during Spring (0.15 μM) and maximum during Summer (0.50 μM; $p \leq 0.05$), significantly different from Autumn and Wet conditions concentrations that were similar between them ($p > 0.05$). Average ammonium concentration was also minimum during Spring (0.9 μM) and maximum during Wet conditions (4.5 μM; $p \leq 0.05$), significantly different from Summer and Autumn values that were similar between them ($p > 0.05$). Average nitrate + nitrite concentration during Wet conditions was significantly higher (3.1 μM) than that obtained in the remaining seasons (p ≤ n.d5). From the Redfield ratios (not shown), nitrogen was the limiting nutrient (N:P ratio <16) for all seasons except during the Wet conditions survey, associated with an augment of ammonium and nitrate relative to phosphate particularly at WB1 and WB5-R, respectively (Fig. 3). In relation to N:Si ratio, nitrogen was the limiting element during Spring and Summer field surveys (N:Si ratio <1) due to an augment of silicate relative to nitrogen, while silicate was the limiting nutrient (N:Si ratio >1) during Autumn and Wet conditions field surveys. Average chlorophyll *a* concentration during Summer survey was significantly higher (0.8 μg/L) during the remaining field surveys ($p \leq 0.05$). A maximum of almost 3 μg/L was obtained during this season.

To discriminate the factors that best describe the seasonal variability of data for the overall sampled stations, a PCA analysis was applied (Fig. 5). Only water temperature, salinity, ammonium, nitrate + nitrite, phosphate and chlorophyll *a* were selected, since dissolved oxygen, pH, silicate and total suspended solids concentrations did not show significant seasonal differences. In this analysis, the three main components explain *ca.* 79% of the variance of the results. PC1 accounts for 38% of the variance, PC2 for 26%, while PC3 for 15% (Fig. 5).

The first factor is explained by the minimal salinity and water temperature in the Wet conditions survey together with the highest concentrations of nitrate + nitrite, opposed to the conditions found during the Summer survey. The second factor can be explained by the lowest ammonium and phosphate concentrations during the Spring survey. The third factor is explained by the highest chlorophyll *a* concentrations against the lowest ammonium concentration.

Data of temperature, salinity, pH, dissolved oxygen and chlorophyll *a* acquired by the RTO in WB2 at high frequency (sampling interval of 15 min) during the four field surveys are compared in Fig. 6 to better understand the environmental settings during and before these surveys. Fig. 7 shows the data records for the Winter of 2019 to contextualize the April 2019 field survey period. It is important to remark that only water temperature, dissolved oxygen (concentration in mg/L) and chlorophyll *a* concentration were presented during this period, since the pH and conductivity sensors were out of work and, as a result, the saturation percentage cannot be derived without salinity correction. In general, the data ranges acquired by RTO were similar to the ones recorded during the seasonal field surveys conducted over the semidiurnal tidal cycles.

Water temperature variability was well marked, confirming the seasonal signal. As can be seen from Fig. 6A, values were around 21 °C in the first survey by the end of May. In the Summer survey, led during September, temperature decrease was found some days before the field survey, from about 22 to 20 °C. This can be associated to an upwelling event on the adjacent coast, as confirmed by wind direction and velocity records under westerlies (Figure SM 2), and by weekly satellite imagery of SST and chlorophyll *a* for the period between 14 and 21 September (Figure SM 3). During this period, in the coastal ocean adjacent to Ria Formosa (~19 °C) the low water temperature was accompanied by higher chlorophyll *a* concentration (1–1.5 μg/L) when compared to offshore values (>22 °C and <0.5 μg/L, respectively; Figure SM 3). During the Autumn field survey in October, the influence of easterlies was predominant (Figure SM 2) and, consequently, water advection from the Gulf of Cadiz left a signature of warmer water on the coast (Figure SM 3). Regarding the Wet conditions survey (Fig. 7A), water temperature ranged between 17 and 19 °C in the first days of April, and then decreased to values around 16 °C between 5 and 12 April, which encompasses the field survey period. However, no upwelling signature was observed in the SST satellite images (Figure SM 3). During the same period, chlorophyll *a* concentration ranged between 1.5 and 2 μg/L in the adjacent coast, with lower values (<0.5 μg/L) offshore (Figure SM 3). In 2017 period (Fig. 6B), salinity ranged between 36 and 36.5, with higher values during Summer (July–August *ca.* 37). Considering the sampled surveys, a maximum was reached in September, while lower values were obtained in Wet conditions. Unfortunately, the RTO did not record salinity data during the Wet conditions survey, but the values were <36 during February (Fig. 7B). pH variability was narrow (7.9–8.2) with the minimum values obtained during the Summer and the maximum during the Autumn survey (Fig. 6C). Despite the fact that 2017 surveys presented relatively similar dissolved oxygen values between them (Fig. 6D and E) and lower than the Wet conditions survey of April 2019 (Fig. 7C), the wider range was found during Summer conditions. Values below 5 mg/L (Figs. 6D and 7C), the minimum

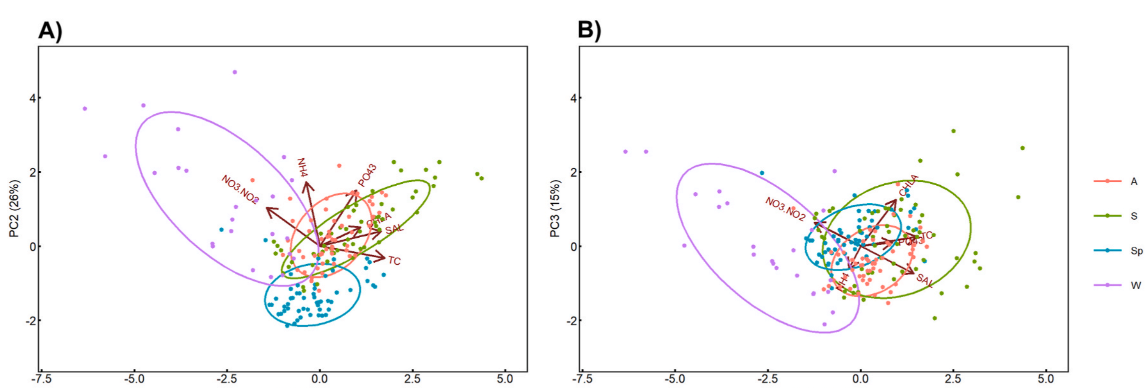

Fig. 5. – Principal component analysis. A) PC1 vs. PC2 and B) PC1 vs. PC3 applied to the data (water temperature – TC; salinity – SAL; nutrients – nitrate + nitrite (NO3.NO2), ammonium (NH4), phosphate (PO43); chlorophyll a – CHLA) for each seasonal survey (Sp – Spring; S – Summer; A – Autumn; W – Wet conditions).

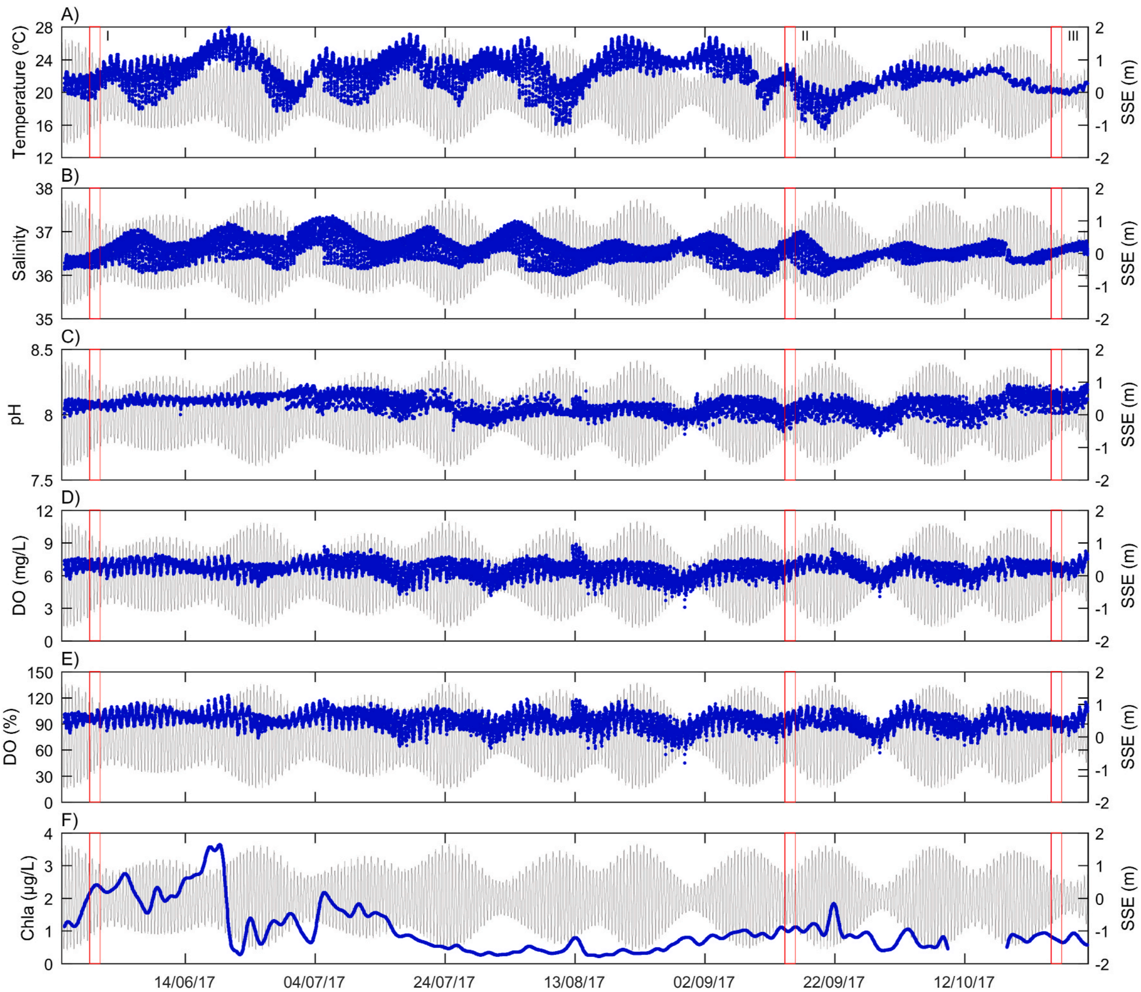

Fig. 6. – Time series of water temperature (A), salinity (B), pH (C), dissolved oxygen in concentration (D) and in percentage of saturation (E) and chlorophyll a concentration (F) recorded by the RTO, encompassing the period of the Spring (I), Summer (II) and Autumn (III) field surveys performed in 2017 (red boxes). The gray curve represents the sea surface elevation due to the tide (SSE, right-hand axis).

concentration to support aquatic life (EPA, 2000; Vaquer-Sunyer and Duarte, 2008) were scarce. Most of the values were within the range 6–8 mg/L, corresponding to 80–110%, which represents well-oxygenated waters, as observed in the field surveys periods. The chlorophyll *a* concentration recorded by the RTO reflected the typical seasonal variability, with the highest concentrations in the Spring survey (*ca.* 2 μg/L; Fig. 6F) that continuously decrease until the Wet conditions survey, when the minimum (mean of 0.4 μg/L) occurred (Fig. 7E).

4.2. Classification of the water bodies based on water quality indexes

The whole dataset from the field surveys performed during 2017 and 2019 and historical datasets were used to classify the water quality in terms of trophic and chlorophyll *a* indexes along the years (Table 3). Considering the parameters available in each historical dataset (Table SM 1), it was only possible to apply these indexes to Benoliel (1984, 1985, 1989) and Falcão (1997) datasets. From TRIX, it is possible to observe an improvement of the water quality at WB2, from “Moderate” in 1980 to “High” in 1984 and maintained in the present study. The new dataset showed that Ria Formosa water bodies were classified as “High” (oligotrophic state), except for the WB5, that presented a classification of “Good” (mesotrophic state; Table 3). BS, representative of a boundary station showed the lowest TRIX value, which denotes the best water quality, despite within the same classification of “High” quality (not shown). Regarding chlorophyll *a* status, based on the benchmarks defined by Brito et al. (2012b), shown in Table 2 for southern coastal lagoons, and the similar reference value for Ria Formosa, water mass type A4 (open coastal lagoon; 5.3 μg/L), the results indicate a “High/-Good” classification at all the sampling stations located in the Ria Formosa, even when considering the historical data from the 80’s (Table 3).

5. Discussion

Given the lack of recent information to assess the overall water quality status of Ria Formosa coastal lagoon water bodies and to predict future scenarios in the context of potential exposure to an intensification of anthropogenic pressures and climate changes, the present work intended to contribute to fulfil this gap of knowledge by providing recent data relative to complete tidal cycles sampling, along the different water bodies, conducted in different seasonal periods, despite considered limited in terms of temporal coverage (less than two years, low confidence level; Table SM 2). Even representing only four temporal surveys, synoptically conducted at seven sampling sites, these data are representative of present environmental conditions under different seasons, and water masses defined along Ria Formosa, since in this system striking horizontal and vertical gradients are not observed.

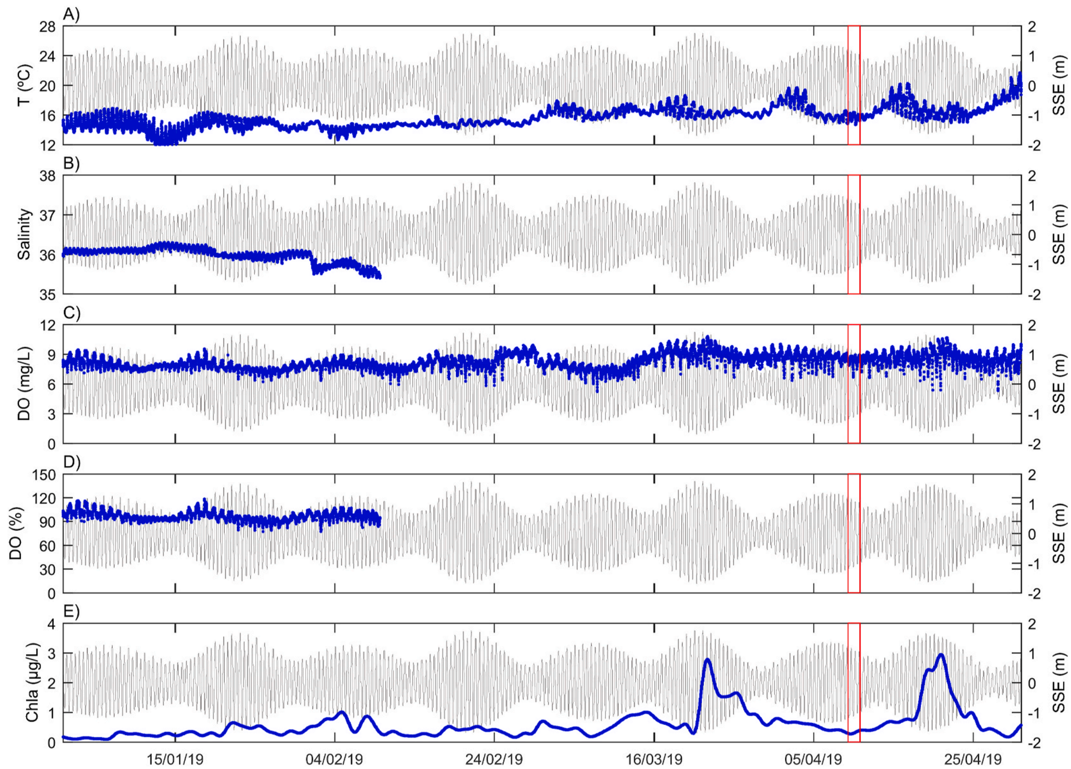

Fig. 7. – Time series of water temperature (A), salinity (B), dissolved oxygen in concentration (C) and in percentage of saturation (D) and chlorophyll a concentration (E) recorded by the RTO, encompassing the Winter season and the period of the Wet conditions field survey performed in 2019 (red box). The gray curve represents the sea surface elevation due to the tide (SSE, right-hand axis).

Table 3
Comparison of TRIX and chlorophyll *a* status in the Ria Formosa water bodies between different datasets.

WB	Datasets									
	1980		1981–83		1984		1985–86		2017–19	
	TRIX	Chla index	TRIX	Chla index	TRIX	Chla index	TRIX	Chla index	TRIX	Chla index
1	–	–	–	–	–	–	–	–	H	H/G
2	M	H/G	G	H/G	H	H/G	–	–	H	H/G
3	–	–	–	–	H	H/G	H	H/G	H	H/G
4	–	–	–	–	–	–	H	H/G	H	H/G
5-R	–	–	–	–	–	–	H	H/G	H	H/G
5	–	–	–	–	–	–	–	–	G	H/G

5.1. Spatial and short-term variability of the water quality in Ria Formosa water bodies

The factors that better explain the spatial variability can be associated with the dissimilar behavior found at WB1, WB2, WB5-R and WB5, that are influenced by distinct processes along the seasonal cycle. The shallowest stations located at both the edges of the lagoon (WB1 and WB5) presented the most dissimilar behavior from the selected water bodies of the Ria Formosa, exhibiting significant differences in relation to the seawater boundary station (BS), as observed in Fig. 3. Generally, those two shallowest sites demonstrate the importance of internal benthic **processes** in shallow systems, driven by two main processes: i) diffusion from the sediments, where a release of phosphate and silicate from the bottom (at WB5) can be more intense during Summer conditions, as found previously in sediments from Ria Formosa (Falcão and Vale, 1998; Falcão et al., 2006; Serpa et al., 2007) or in other coastal systems (e.g., Leote et al., 2016; Nixon, 1982; Oehler et al., 2019; Rutgers van der Loeff et al., 1984; Wang et al., 2015; Wu et al., 2014); ii) organic matter input due to runoff and/or resuspension and diffusion from sediments, and remineralization after a period of rainfall at WB1, when the highest ammonium concentration was recorded (Fig. 3F). In fact, at those very shallow areas (<30 cm in depth in low water), the current velocity is less pronounced, contributing to a lower dissipation of energy (Dias and Sousa, 2009). At those areas, velocities lower than 0.3 m s^{-1} have been reported (Soares et al., 2001; Duarte et al., 2008), significantly lower than those that may attain up to 1.6–2.2 m s^{-1} at the main inlet (Pacheco et al., 2007). It is plausible that under weak currents, higher rates of accumulation of organic matter are favored. Hence, at the shallowest zones, internal processes coupling benthic-pelagic interactions (e.g., remineralization, bioturbation, diffusion from the sediments and resuspension) are potentially intensified, as reported by other authors either for Ria Formosa (Brito et al., 2009, 2010; Falcão and Vale, 2003) or for other coastal (lagoons) systems (Karlson et al., 2007; Thouzeau et al., 2007; Ospina-Alvarez et al., 2014). It is well known that benthic fluxes are influenced by temperature and by other induced physical changes, varying with the sediment grain size, usually with the highest concentrations of organic matter and nutrients in fine-grained sediments rich in silt and clay (Nowicki and Nixon, 1985). The sediments of the shallowest zones are mainly constituted by fine mud, where nutrients fluxes, and ammonium in particular, are generally higher than in sandy sediments, promoting a release of nutrients from the bottom sediments to the water column, as reported already for Ria Formosa (Falcão and Vale, 1998; Falcão et al., 2006; Serpa et al., 2007) and for other coastal lagoons (e.g. on the ocean coast of Rhode Island, U.S.A; Nowicki and Nixon, 1985; and at Northern Galician Rias, Spain; Ospina-Alvarez et al., 2014). In addition, in mesotidal systems, tidal water movement promotes the sediment–water exchange of nutrients in intertidal areas, since the flowing water during both flood and ebb tides can interact with the sediment pore water (Caetano et al., 1997). Tidal flooding in intertidal sediments of coastal systems point out to alterations of pore water nutrients, mainly during the first minutes of inundation. By that time, sediments may be resuspended, and seawater mixed with porewater of surface sediment layers, changing the composition of the surface water, as reported either in Ria Formosa (Falcão and Vale, 1998; Falcão et al., 2009) or in other coastal systems, such as the Northern Galician Rias (Ospina-Alvarez et al., 2014).

Typical variation of the nutrients concentration along a semidiurnal tidal cycle in antiphase with the sea surface elevation (as demonstrated for silicate in Fig. 2A), with concentrations increasing during the ebb period, may also result from the dilution effect felt during the flooding period, when lagoon waters mix with oceanic waters. These nutrient providing processes also control the biological processes and photosynthesis in particular at WB5, as expressed by the extreme variation of dissolved oxygen along the tidal cycle (Fig. 3C).

WB5-R and WB2 differed from the remaining water bodies. In particular, the Gilão River, located at Tavira, had a significant contribution regarding the variability of nitrate + nitrite concentrations at WB5-R, particularly after the rainfall period (Fig. 3G). Runoff over agriculture fields, may provide waters enriched in fertilizers, pointed out as the main sources of nutrients in this lagoon (Barbosa, 2010; Newton et al., 2003; Newton and Mudge, 2005). By the other end, the highest chlorophyll *a* concentrations found at WB2 (Fig. 3H) can be associated with more favorable conditions for phytoplankton growth, particularly at an inner and shallow area involved by an extensive saltmarsh area (Cravo et al., 2020).

The TRIX index along with the chlorophyll *a* index (Table 3) revealed an overall "High/Good" water quality status at all the sampling stations located in the Ria Formosa, even at the WB2, where the maximum of chlorophyll *a* concentration was obtained. This result suggests that the anthropogenic pressure in this lagoon is not particularly high, in opposition to what is currently found in other coastal systems, like large estuaries in Europe (e.g. Tagus estuary, Portugal; Rodrigues et al., 2020), or in microtidal lagoons in the Mediterranean, with limited tidal water renewal such as Venice lagoon (Italy; Çevirgen et al., 2020) and Remolar and Ricarda coastal lagoons (Spain; Cañedo-Argüelles et al., 2012), or even in macrotidal lagoons in the North-western of the South Atlantic Ocean, such as Jansen Lagoon (Northern Brazil; Cutrim et al., 2018). In such coastal systems, inputs of organic matter and/or nutrients can be large, which leads to water quality below "Good" status and to environmental problems, such as eutrophication, that are not evident in Ria Formosa, due to the high water renewal during each tidal cycle (Fig. 2), as reported by Rosa et al. (2019).

The temporal variability of results is related to meteorological conditions, including temperature, precipitation intensity, wind regimes and patterns, and oceanographic processes occurring on the adjacent ocean, which controlled the fluxes and pathways of key processes, also interplaying with primary production. Within a trend of increasing atmospheric temperature measured at Faro along the last 50 years (Figure SM 1 B in the Supplementary Material), data for the four surveys revealed that the seasonality was less evident than could be anticipated, even though some key points can be remarked. The short-term temporal data analysis revealed the importance of the environmental settings on the physical, chemical and biological processes in each season. The physical process of input of material by sediments diffusion and/or runoff during the Wet conditions survey and the phytoplankton growth on Summer showed to have a major role on the water quality of Ria Formosa, as confirmed by PC1 in Fig. 5A.

Information acquired *in situ* during the field surveys, particularly at WB2, were validated by the RTO data and clearly showed a seasonal signal in water temperature and salinity records, with higher values during Summer and lower during Autumn/Wet conditions surveys. Both parameters affect the solubility of the dissolved oxygen, which was lower during Summer, decreasing the pH during this period (Figs. 6 and 7).

During Wet conditions survey, the maximum ammonium and nitrate + nitrite concentrations were found, likely associated with runoff and inputs of organic matter lead by the preceding rain period (Table 1), while phytoplankton growth was limited by solar radiation, as reflected by the low average chlorophyll *a* concentrations during this period (Fig. 4H). During the Spring survey, phytoplankton did not grow as a result of nutrients limitation, as confirmed by the lowest nutrient and chlorophyll *a* concentrations (Fig. 4H and PC2 in Fig. 5A).

During the Summer survey, the low concentration of nutrients may echoed the increase of their consumption by phytoplankton, as suggested by the higher concentrations of chlorophyll *a* during this season (Fig. 4H and PC3 in Fig. 5B). Seasonal cycles with a maximum primary biological productivity during Summer were previously reported in this coastal lagoon (Assis et al., 1984; Falcão et al., 1991), associated with optimal ranges of temperature and solar radiation, particularly in the inner zones (Barbosa, 2010). Phosphate exhibited the highest concentrations during Summer (Fig. 4D), which can be explained by its peculiar chemical behavior and the importance of internal processes within the lagoon under elevated temperatures, as mentioned before. Other processes can explain the increase of nitrate + nitrite during the Summer survey at BS over the flood period (Fig. 2B). An upwelling event provided it, mostly evident at the station in permanent connection with the coastal ocean (Fig. 1), suggesting that nitrogen was imported from the adjacent ocean during the flooding period. The latter promoted a shift in the Redfield ratio, a behavior already reported by other authors in this coastal lagoon (Alcântara et al., 2012; Barbosa, 2010; Cravo et al., 2014, 2019; Rosa et al., 2019). Upwelling events can be frequent on the south coast of Portugal (García-Lafuente et al., 2006; Relvas and Barton, 2002), and represent an important forcing mechanism to increase the biological productivity within the system (e.g. Rosa et al., 2019). This fact may also contribute to explain the increase of chlorophyll *a* inside the Ria Formosa, particularly through the main channel close to the inner WB2 during the Summer survey, as supported by the PC3 from PCA analysis (Fig. 5B). In this coastal lagoon, as already reported in previous studies (e.g., Cravo et al., 2014; Rosa et al., 2019), nitrogen was commonly the limiting nutrient as typical of marine coastal waters (Barik et al., 2017; Howarth and Marino, 2006; Paerl, 2018). Nevertheless, due to the present increasing nutrient loads in many impacted coastal systems, N:P ratio has been substantially increasing and exceeding the Redfield ratio of 16:1 (Glibert et al., 2014; Wang et al., 2021). In this study, P-limitation only occurred during the Wet conditions survey, influenced by the input of ammonium at WB1 and nitrate at WB5-R that distorted the nutrients ratio, also with impact on the N:Si ratio, when silicon became limiting.

5.2. Long-term temporal evolution of Ria Formosa water quality

It is well known that there is a lack of sufficient data to perform a robust evaluation of long-term temporal evolution of water quality in coastal systems (Cravo et al., 2020). In a long-term temporal evolution perspective, the comparison of the data obtained in the present work with historical datasets, allows to assess the temporal variability of the water quality parameters of Ria Formosa water bodies along almost 40 years. However, it is important to note that the datasets used comprise mostly scatter data, which could represent a limitation of this analysis. For this reason, the confidence level criteria defined by HELCOM (2019) was considered for all the datasets. Except for the period of 1981-83 and 1985-86 when the confidence level is high, data acquired in the four temporal surveys is considered of low confidence level like in 2010 (with only one sampling survey), and of intermediate confidence level in 1980, 1984 and 1987–1989. For this reason, data are not sufficiently robust and can limit the water quality evolution assessment or even its intra-annual variability. Even though, as the present results cover different seasonal conditions, these can be valuable and representative of recent conditions, allowing a comparison along time.

There are several nutrient and water quality criteria used by the EU member states, which includes the use of different nutrients (and its forms) and statistical metrics, which may be preventing the good ecological status of the coastal systems. For this reason, there is a need to use consistent approach to address properly water quality and effectively support the management of coastal systems to achieve the good ecological status (Poikane et al., 2019). In Portugal, under the WFD (Brito et al., 2012b), the 90th percentile was adopted for chlorophyll *a* during the growing season (between February and October), while APA – Agência Portuguesa do Ambiente (2021) defined the 90th percentile of the annual data for nutrients. However, the mean and/or median have been widely used in the nutrient classification in the EU member states (Poikane et al., 2019). For these reasons, Table 4 shows the statistical metrics for all the datasets, including range, average, 90th and 10th percentiles, along with comparison with thresholds/metrics recently defined by EEA (2021) and APA – Agência Portuguesa do Ambiente (2021).

In this long-term temporal evolution, it is important to contextualize the meteorological conditions, and precipitation in particular, measured in Faro in the last 50 years (Figure SM 1 A) is being decreasing. Rainfall for 2017 to 2019 was markedly lower than 1988–1989 records, when the study of Newton (1995) was conducted.

Fig. 8 illustrates the concentrations of dissolved oxygen, phosphate, silicate, DIN and chlorophyll *a* over almost 40 years of data. To have a spatial coverage comparable to previous works, data corresponding to BS and WB3 were included together as WB3, along with WB5-R and WB5 as WB5. Moreover, extreme silicate (>100 μM) and DIN concentrations (>200 μM) from the 1987-89 historical dataset (Newton, 1995) were not considered. Data comparison suggests that the water quality of the Ria Formosa has improved along the last 40 years. This water quality improvement is evidenced by the general decreasing trend in the nutrients and chlorophyll *a* concentrations for all water bodies in the lagoon (Fig. 8), showing values close to the lowest thresholds imposed

Table 4

– Statistical parameters for nutrients and chlorophyll-a for comparison with water quality limits referred for European waters by regulating authorities (EEA, APA for WFD). EEA classifications: V.L. – Very Low concentrations, L – Low concentrations, M – Moderate concentrations, H – High concentrations, V.H. – Very High concentrations. RIM and EQR classifications (for details please see section 3.6): H – High, G – Good, M – Moderate. R.V. means Reference Value. n.d. - not detectable. PO_4^{3-}* – for EEA limits mean annual of TP is considered. Chla** – represents only the growing season (between February and October).

Parameter	Dataset	N	Max	Min	Average	90%	10%	EEA (2021)					RIM		EQR	
								V.L.	L	M	H	V.H.	R.V.		R.V.	
NH_4^+ (μM)	**2017–19**	191	15.0	0.1	2.5	4.0	0.5						**28.5**	**H**		
	2010	14	8.4	0.5	3.4	7.0	0.6							**H**		
	1987–89	278	31.9	n.d.	3.1	7.4	0.2							**H**		
	1985–86	–	–	–	–	–	–							**-**		
	1984	48	4.3	0.7	1.9	3.3	1.0							**H**		
	1981–83	59	10.2	0.7	1.9	3.3	0.8							**H**		
	1980	11	6.1	1.5	3.5	5.9	1.5							**H**		
$NO_3^- + NO_2^-$ (μM)	**2017–19**	191	9.9	n.d.	0.9	1.7	0.2	**< 5**	**5–10**	**10–20**	**20–40**	**> 40**	**43**	**H**		
	2010	14	12.7	2.4	7.2	12.3	3.3							**H**		
	1987–89	295	331.1	n.d.	14.6	39.7	0.5							**H**		
	1985–86	132	6.8	0.3	1.1	2.9	0.4							**H**		
	1984	71	17.3	0.1	2.3	4.1	0.8							**H**		
	1981–83	92	239.4	n.d.	13.0	27.6	0.7							**H**		
	1980	9	48.2	7.4	22.5	48.2	7.4							**G**		
DIN (μM)	**2017–19**	191	16.0	0.3	3.4	5.8	1.1	**< 5**	**5–10**	**10–20**	**20–40**	**> 40**				
	2010	14	21.0	5.0	10.6	18.1	5.5									
	1987–89	345	354.9	n.d.	15.4	40.9	0.6									
	1985–86	132	6.8	0.3	1.1	2.9	0.4									
	1984	91	18.0	0.1	2.9	5.5	0.3									
	1981–83	94	100.2	0.1	11.4	25.2	0.6									
	1980	11	54.3	11.1	25.2	52.9	11.2									
PO_4^{3-} (μM)*	**2017–19**	191	0.9	0.1	0.3	0.7	0.1	**< 0.5**	**0.5–1.0**	**1.0–2.0**	**2.0–4.0**	**> 4.0**	**1.9**	**H**		
	2010	14	0.4	0.1	0.2	0.4	0.1							**H**		
	1987–89	315	4.0	n.d.	0.8	1.4	0.2							**H**		
	1985–86	132	2.0	0.1	0.8	1.3	0.2							**H**		
	1984	96	0.6	n.d.	0.2	0.3	0.1							**H**		
	1981–83	95	1.0	n.d.	0.2	0.4	0.1							**H**		
	1980	11	0.9	0.1	0.4	0.9	0.1							**H**		
SIO_4^{4-}(μM)	**2017–19**	191	11.2	0.7	3.8	7.4	1.1									
	2010	14	20.5	2.0	8.6	19.1	2.8									
	1987–89	342	1200.8	n.d.	35.8	62.0	2.8									
	1985–86	132	13.1	0.2	3.6	6.1	1.3									
	1984	95	5.9	1.3	2.9	4.4	1.6									
	1981–83	86	12.4	1.0	3.2	5.9	1.3									
	1980	11	10.8	3.5	7.9	10.7	3.6									
Chla (μg/L)**	**2017–19**	191	2.9	n.d.	0.6	1.2	0.1								**5.3**	**H**
	2010	–	–	–	–	–	–									**-**
	1987–89	–	–	–	–	–	–									**-**
	1985–86	108	5.7	0.2	1.2	2.0	0.4									**H**
	1984	87	4.1	0.7	1.5	2.5	0.8									**H**
	1981–83	34	3.9	0.5	1.9	3.1	0.8									**H**
	1980	10	3.3	1.5	2.3	3.3	1.5									**H**

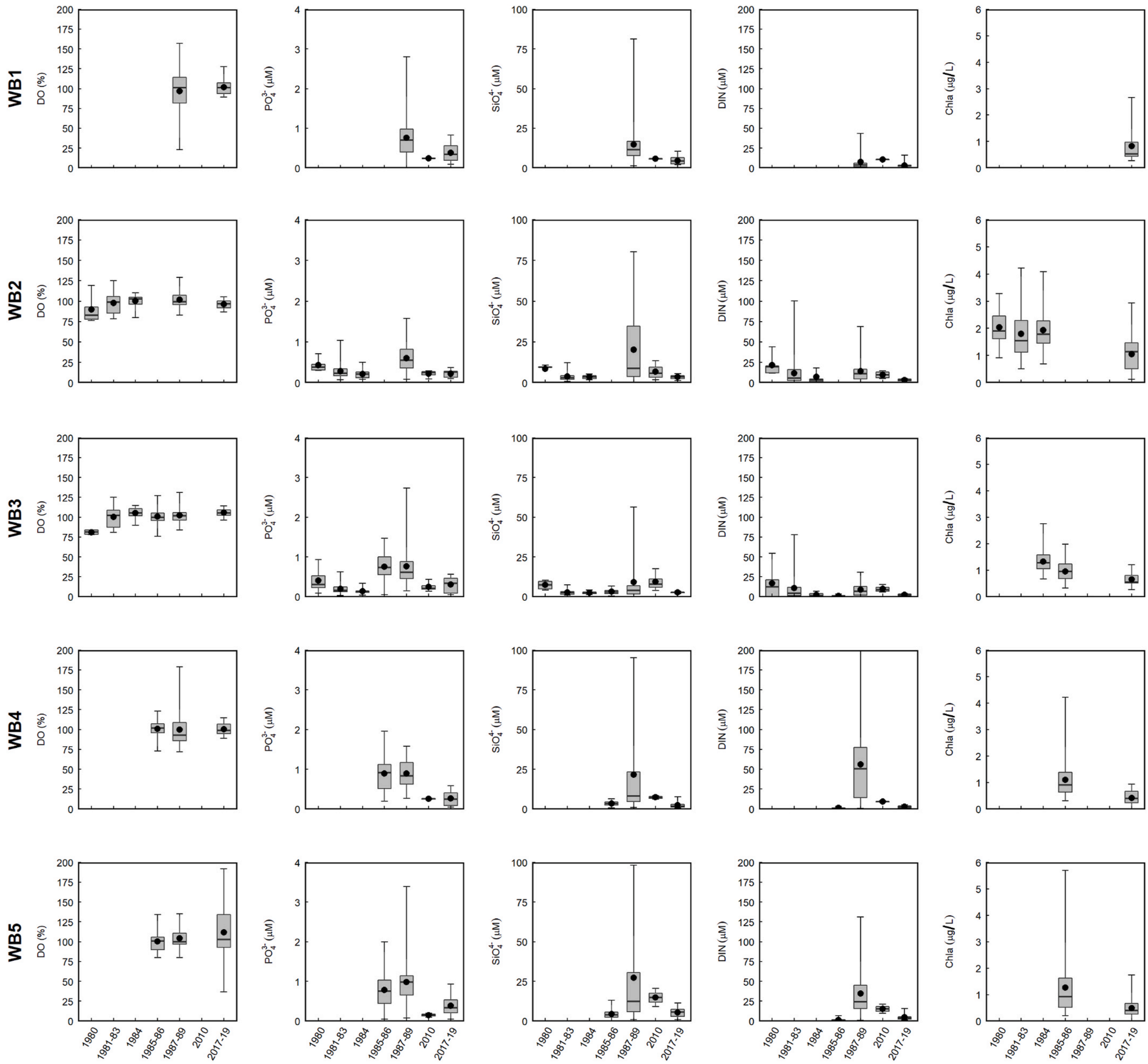

Fig. 8. – Boxplot of dissolved oxygen, phosphate, silicate, DIN and chlorophyll a concentrations in the five water bodies of Ria Formosa along different periods. In the boxplots, the solid line represents the median, the black dots represent the average, the lower and upper hinges are the 25% and 75% percentiles, whiskers represent the minimum and maximum values. The datasets used in this analysis were retrieved from: 1980 – Benoliel (1984); 1981/83 – Benoliel (1989); 1984 – Benoliel (1985); 1985/86 – Falcão (1997); 1987/89 – Newton (1995); 2010 – APA – Agência Portuguesa do Ambiente (2010); 2017/19 – present study.

by the EEA (very low concentration of TP < 0.5 μM, and DIN <5 μM, for winter, when the concentration of nutrients are the highest due to a decrease of phytoplankton consumption). In fact, during the Wet survey, after the rainfall period, the mean of DIN concentration increased, but never exceeded the classification of low concentration (5–10 μM). Within the context of WFD, APA – Agência Portuguesa do Ambiente (2021) stated mean reference values for Ria Formosa (type A4, open coastal lagoon; ammonium: 28.5 μM, nitrate + nitrite: 43 μM, phosphate: 1.9 μM, and chlorophyll *a*: 5.3 μg/L). These values are much higher than the ones recorded in the present study, confirming the low nutrients and chlorophyll *a* concentration and the high-quality classification of the water masses (Table 4). Considering the RIM along time (Table 4), a "High/Good" status classification was attained for the overall period 1980–2019. The decreasing trend in the concentrations of nutrients and chlorophyll *a* was particularly evident since the 1987–1989 dataset, accompanied by a marginal increase in the dissolved oxygen (Fig. 8). The nutrients decreasing trend was clearer at WB5. The maximum nutrient concentrations recorded during the 1987–1989 dataset can be related with the maximum precipitation recorded during this time (see Figure SM 1 A in the Supplementary Material section), and consequent increased continental inputs by land runoff. Considering that silicate is usually used as a freshwater tracer (both for river inputs and submarine groundwater discharges; Frings et al., 2016; Sospedra et al., 2018; Oehler et al., 2019), the influence of rainfall on silicate concentrations is also clear over the last 40 years. In particular, wetter periods resulted in high silicate concentrations

(1987-89 and 2010 datasets), while low silicate concentrations were found during drier periods (1980, 1981–83, 1984, 1985–86, and 2017-19 datasets; see Fig. 8 and Figure SM 1 A).

Moreover, several alterations occurred in this coastal lagoon and its watershed over the past 40 years, which can explain the improvement observed in the water quality parameters. Several morphological interventions were made to improve the water circulation and exchange with the ocean, namely the relocation/opening of the Ancão inlet in 1997 (Vila-Concejo et al., 2004) and in 2015 (Jacob and Cravo, 2019), the relocation of the Fuzeta inlet in 1999 (Vila-Concejo et al., 2004), the dredging of the main channels in 1999 and 2000 (Newton and Icely, 2002; Ribeiro et al., 2008), and more recently the relocation of the Cacela inlet in 2015. The implementation of Urban Waste Water Treatment Plants since the 90's (Cravo et al., 2015) and an improvement and/or upgrade of urban effluents treatment along the last decade and the comply of the European Urban Waste Water Treatment Directive (EEC, 1991a) also contributed to improve the water quality (Barbosa, 2010; Cravo et al., 2015; Ferreira et al., 2012). Additionally, we believe that the decrease in the use of fertilizers in agricultural practices to comply the Nitrate Directive (EEC, 1991b) also contributed to decrease nitrogen in this ecosystem (Cravo et al., 2015; Stigter et al., 2006).

This trend of water quality amelioration in Ria Formosa can contrast to many other coastal lagoons and ecosystems, where anthropogenic pressure led to a degradation of these productive systems (e.g., Nichupté Lagoon System, México; Romero-Sierra et al., 2018; and Venice lagoon, Italy; Çevirgen et al., 2020). However, the microtidal Mar Menor Lagoon in the Mediterranean Sea has also recording an improvement of water quality in the last two decades due to reduction of nitrate discharges (Pérez-Ruzafa et al., 2019), after the water quality degradation by eutrophication observed in the mid 1990's caused by changes in the agricultural practices in the lagoon watershed and the strong increase in nutrient loads (Pérez-Ruzafa et al., 2019, 2020). The Thau lagoon (France) is another example of a coastal system recovered from eutrophication and anoxic events, which resulted from the improvement of the WWTP, decreasing substantially the nutrients inputs into the lagoon (Derolez et al., 2020).

It is important to remark that the south of Portugal has similar weather conditions as found on the Mediterranean coast that has been identified as one of the most responsive regions to climate change. There, the records show a significant decrease in the mean precipitation (Herrmann et al., 2014), together with a surface water warming, a salinity increase (Vargas-Yáñez et al., 2017), and a decrease in nutrient availability (Herrmann et al., 2014) that ultimately will impact phytoplankton (Temino-Boes et al., 2021) and intrinsically the primary productivity of this coast.

6. Conclusions

Ria Formosa water quality was assessed throughout all the different water bodies under four periods of the year over complete semidiurnal tidal cycles. The achieved data was complemented with real time data acquired at high frequency from a multiparametric probe deployed at a main channel in the innermost water body, where the anthropogenic pressure is higher. Data analysis revealed that this coastal lagoon presents a high/good quality considering the quality indexes (TRIX and chlorophyll *a*), even at WB2, where the anthropogenic pressure is maximum. This is due to the high-water renewal rate during each semidiurnal tidal cycle.

Spatially, the five water bodies identified in Ria Formosa were covered synoptically and no striking differences were found between them. Yet, those located at the edges of the lagoon (WB1 and WB5) presented the largest variability and highest concentration of nutrients, except for nitrate that was maximum at the estuarine station influenced by the Gilão River, even with low flow rate. The dissimilar behavior of the border stations is associated with their shallowness, restricted water circulation and potentially favored higher rates of organic matter accumulation. All these factors co-promoted the intensification of internal processes, coupling benthic-pelagic processes, namely remineralization and diffusion from the sediments that, ultimately, control the biological processes.

Wet conditions and Summer were the most distinct sampling periods, despite seasonal variability between Spring and Autumn was lower than anticipated. In a future study, and to attain a more robust signature of the seasonal variability, more intense sampling frequency along the year should be considered. The precipitation event that preceded Wet conditions survey influenced the nutrients increase, nitrate at the estuarine site and ammonium at the western edge of Ria Formosa. In opposition, during Summer survey concentrations were generally low, associated with nutrient consumption by the primary producers, paralleled by the highest concentrations of chlorophyll *a* during this season. Nevertheless, phosphate and silicate to some extent on the shallowest areas showed a different behavior, since their peculiar chemistry depend on temperature, that promotes their diffusion from the sediments to the water column under high temperatures, as seen in WB5 on the eastern edge of Ria Formosa.

The comparison between 2017 and 2019 data and historical datasets, although the low confidence level rating due to limitation of sampling frequency, showed that there has been a water quality improvement in Ria Formosa, reflected in a general decrease of the nutrients and chlorophyll *a* concentrations in all water bodies together with a marginal increase of dissolved oxygen. This water quality improvement can be associated with morphological changes in the coastal lagoon that increased the circulation and water exchange with the ocean, the upgrade and increase of operating wastewater treatment plants, and the decreased use of fertilizers in agriculture, under the Urban Waste Water Treatment and Nitrate Directives, respectively. This was reflected by the "High" quality TRIX trophic index, except at WB5 classified as "Good". This ecosystem exhibited a higher water quality than coastal systems with restricted water circulation and tidal renewal like in the Mediterranean and/or greater loads of organic matter and nutrients. Moreover, data show that a decrease of precipitation has an important effect upon the water quality. During periods of precipitation, increases of nutrients as well as organic matter occur having impact on the oxygen levels. However, if a decreasing rainfall trend persists in the next future, an impoverishment of nutrients in Ria Formosa could be expected, with impact on the overall biological productivity, including on bivalves' production so important in this ecosystem.

These data provide the most recent and updated picture of the water quality conditions in Ria Formosa as a whole, which contributes to a better understanding of the functioning of this system. This provides data on recent conditions that can be useful to further validate numerical hydrodynamic-biogeochemical models as useful tools to simulate and anticipate the susceptibility of Ria Formosa to future scenarios of global changes. Given their potential effects, to understand the past and present conditions to predict the future and guarantee a sustainable management of coastal lagoon systems is a key issue for the socio-economic and environmental development of these systems worldwide, which is imperative for building knowledge-based societies. In future studies, to get more robust temporal analysis, an intensification of sampling campaigns will be needed.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Alexandra Rosa reports financial support was provided by Fundação para a Ciência e Tecnologia. Alexandra Rosa reports a relationship with Oceanic Observatory of Madeira that includes: employment.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.csr.2022.104804.

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