Understanding the biogeochemical buffering capacity of estuaries relative to climate change and anthropogenic inputs

UBEST

Report 1

Characterization of the study areas: Tagus estuary and Ria Formosa

Partners

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Abstract

This report provides a general characterization of both the Tagus estuary and the Ria Formosa, the case studies of the project UBEST. The geographic, climatic and socio-economic dimensions are briefly described, and the hydrodynamics, biogeochemical dynamics and pressures affecting the water quality of both systems are characterized in detail. In particular, the main spatial and temporal patterns of the physical, chemical and biological variables over the past decades are characterized. Their main variations are also discussed in the context of the climatic and hydrological variability and of the anthropogenic interventions in the systems.

Keywords: Historical data, Spatial and temporal patterns, Hydrodynamics, Water quality, Tagus estuary, Ria Formosa

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1. Introduction

Estuaries and coastal lagoons are among the most productive ecosystems on Earth and provide multiple ecosystem services (e.g. Barbier *et al.*, 2011). They harbor ecologically important habitats for fish, shellfish and birds and support diverse human activities (e.g. marine transportation, fishing, tourism, and repository waters for domestic wastewater), providing economic resilience to coastal communities and protecting them from natural hazards. The susceptibility of estuarine and coastal systems to climate change and human-induced threats is thus a major concern. These threats may reduce their capacity to buffer the coastal receiving waters from increased nutrients and other contaminants inputs, leading to poor water quality, reducing ecosystems health and, ultimately, affecting all the related social and economic benefits (e.g. Rabalais *et al.*, 2009; Statham *et al.*, 2012). The anticipation of these impacts is mandatory to promote adequate adaptation measures. It requires the integration of both anthropogenic pressures and the systems' response to the physical and climate drivers and may take advantage of "observatories" (Baptista, 2006) that integrate sophisticated monitoring networks and advanced modelling systems, mechanistically relating the ecosystems dynamics with the physical regimes.

In this context, the project UBEST aims at improving the global understanding of the biogeochemical buffering capacity of estuaries and its susceptibility to future scenarios of anthropogenic inputs and climate change, to effectively support the short and long-term management of these systems. UBEST scientific goals will be achieved by the deployment of "observatories" in two Portuguese case studies: the Tagus estuary and the Ria Formosa, a coastal lagoon. These case studies were selected due to their ecological and economic importance both locally and regionally and, simultaneously, due to their very distinct physical and morphological characteristics, which will facilitate the generalization of the conclusions.

This report provides a general characterization of both the Tagus estuary and the Ria Formosa. The geographic, climatic and socio-economic dimensions are described briefly, and more detailed characterizations of the hydrodynamics, biogeochemical dynamics and pressures affecting the water quality of both systems are presented. In particular, the main spatial and temporal patterns of the physical, chemical and biological variables over the past decades are characterized. Their main variations are also discussed in the context of the climatic and hydrological variability and of the anthropogenic interventions in the systems.

The report is organized in 4 chapters besides the present Introduction. A general overview of estuaries and coastal lagoons dynamics, and related pressures and threats is presented in Chapter 2. The main characteristics of the Tagus estuary and the Ria Formosa are presented in Chapters 3 and 4, respectively. Chapter 5 presents the final considerations. Annex I and Annex II summarize some of the main sources of historical environmental data in the Tagus estuary and Ria Formosa, respectively.

2. Estuaries and coastal lagoons: general overview of dynamics, pressures and threats

Estuaries and coastal lagoons are aquatic ecosystems located in the transition between the land and the coastal ocean. These systems present a natural variability dependent on the variation of the several drivers. While common factors affect both types of systems, such as the tides, freshwater input, wind stress and thermal equilibrium at the surface, the driver's behavior varies as a function of the geomorphological differences between these two environments (Kjerfve and Magill, 1989).

The water quality in estuaries and coastal lagoons depends critically on the circulation inside these systems, the dispersion/dilution of matter, the terrestrial inputs, the mass exchange with the ocean and the residence times. Coastal ecosystems have high rates of primary and secondary productivity (e.g. Barbosa, 2010), either due to the retention of sediments, organic matter and nutrients from land, or by the fertilization from the ocean associated with coastal upwelling events (Kjerfve, 1994; Barbosa, 2010; Cervantes-Duarte *et al.*, 2013). These active, complex and dynamic ecosystems (Falcão and Vale, 2003) are under the influence of several hydrodynamic processes, including the forcing by the wind and tides, which can affect the spatial and temporal variability of physical, chemical and biological processes. In addition, this variability can be intensified by changes in temperature and salinity gradients, due to freshwater influence, and due to the limited access to the adjacent ocean (Nixon, 1982; Nuccio *et al.*, 2003).

Nutrients, along with light availability in the water column, are one the main factors limiting primary productivity in estuaries and coastal lagoons (e.g., McLusky and Elliot, 2004). The processes responsible for nutrient variability in these systems are essentially precipitation, and surface runoff, groundwater inflow, anthropogenic loads, exchanges of water with the coastal zone through the inlets (Falcão, 1996; Ittekot *et al.*, 2000) and recycling processes within the system (Nixon, 1982). The exchanges at the sediment-water boundary are an example of recycling inside the coastal lagoons (Nowicki and Nixon, 1985). This interface has significant effects on the water column processes, particularly due to the tidal movements that cause resuspension of sediments from the bottom (Vale and Sundby, 1987; Falcão, 1996), increasing the availability of nutrients in the water column.

The nitrogen cycle is an important driver of the primary productivity, since the inorganic forms, mostly ammonium, are preferentially assimilated by phytoplankton. The availability of nitrate, the predominant form of inorganic nitrogen in the aquatic environment in oxygenated waters (Libes, 1992), although its consumption by phytoplankton and bacteria (Falcão, 1996) also depends on two fundamental processes: successive nitrification of ammonium released after organic matter decomposition by the presence of bacteria under aerobic conditions and depletion by denitrification under anaerobic conditions.

The dynamics of phosphorus is very complex in intertidal sediments and depends on several factors, such as the macrofauna activity, the benthic primary productivity and the tidal influence (Van Raaphorst *et al.*, 1992). In estuaries and coastal lagoons, the particulate organic phosphorus deposited in the sediments during winter is later mineralized to the most stable form, phosphate. It can then be retained in the sediments, by adsorption to solid particles, or released into the water column, especially in summer when the maximum phosphate concentrations are usually recorded (Nixon, 1982; Falcão, 1996), directly linked to the increase of temperature (Jensen and Andersen, 1992).

In some estuarine and coastal systems, where the biological processes are not dominant, silicate can be considered a conservative nutrient (Statham, 2012). Silicate dynamics is strongly influenced by different drivers. Release processes from the sediments, increasing its availability, are mainly associated with temperature (Capellaci *et al.*, 2012), bioturbation and excretion by benthic organisms (Asmus *et al.*, 2000) and runoff from coastal waters that are rich in silicate (Millero, 1996). Conversely, the removal of silicate from the water is mainly related to diatom dynamics. The increase of the diatom population, typically found after upwelling events (Wefer and Fisher, 1993; Abrantes and Moita, 1999; Moita, 2001), generally leads to the decrease of silicate in many systems (e.g. Ittekkot *et al*, 2000).

Coastal and estuarine ecosystems natural variability can be altered due to several external pressures. The interaction between anthropogenic activities, climatic variability and climate change in these ecosystems is a matter of concern (Cloern and Jassby, 2010; Paerl *et al.*, 2010). Increased human activities in estuaries and coastal systems associated with climate change may increase the vulnerability of these systems, with the complex interactions among them (Rabalais *et al.*, 2009; Figure 2.1).

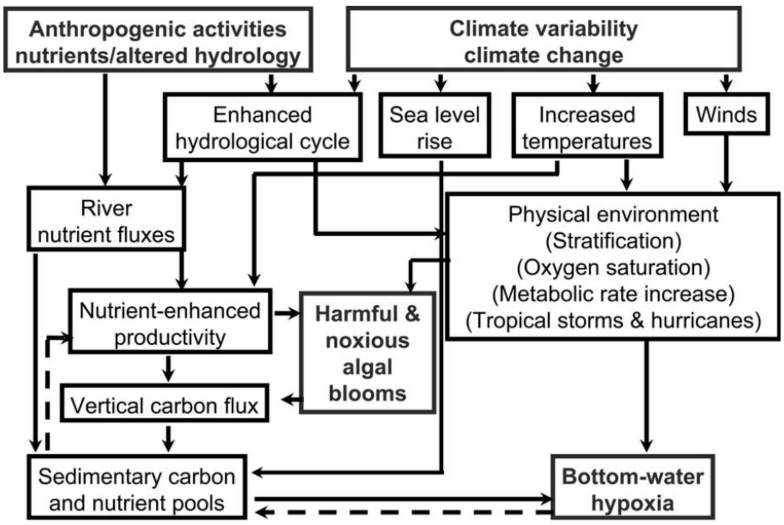


Figure 2.1. Potential physical and hydrological changes resulting from climate change and their interaction with current and future human activities; the dashed lines represent negative feedback to the system (Rabalais *et al.*, 2009).

On the one hand, wastewater discharges that can change the nutrients' balance, dredging and dams that can influence the estuarine hydrodynamics and sediments dynamics, or agriculture that can provide additional non-point sources of nutrients, are examples of human interventions and activities that can threat the estuarine and coastal ecosystems (e.g., Rocha *et al.*, 2002; Zhong *et al.*, 2010; Nayar *et al.*, 2004; Science for Environment Policy, 2012; Sebastiá *et al.*, 2012).

On the other hand, climate change is also matter of concern worldwide, as modifications in air temperature, wind patterns, hydrological regimes and sea level rise may occur (Statham, 2012). Tide-gauge data analysis indicates a global sea level rise during the 20th century that will continue in the near future (e.g. IPCC, 2013, 2014). Predicted values for sea level rise in the Portuguese coast by 2100 are: 0.14-0.57 m (Dias and Taborda, 1988), 0.05-0.20 m (Araújo, 2005), 0.47 (0.19-0.75) m (Antunes and Taborda, 2009) and 0.28-0.42 m (Lopes *et al.*, 2011). Impacts of sea level rise may include: inundation of low-lying coastal areas and erosion of sandy beaches and barrier island coasts, increased tidal prism, with potential changes in the residence times and stratification, landward intrusion of salt water in estuaries and aquifers and displacement of ecosystems and habitats loss, among others (from Pethik, 2001; Lopes *et al.*, 2011). An increase of the average air temperature in the mainland (1-9 ºC) is predicted by the end of the 21st century in Portugal (Miranda *et al.*, 2006; http://portaldoclima.pt/, 2017), and a 3 ºC increase of the maximum summer air temperature is estimated in the coastal areas (Miranda *et al.*, 2006). Rising temperatures may lead to shifts in algal, plankton and fish abundance, affect the oxygen levels and promote the acceleration of the nutrients recycling rates, among others (e.g. IPCC, 2007; Najjar *et al.*, 2010; Statham, 2012). The predicted changes in the hydrological regimes have also a degree of uncertainty, but decreases of the precipitation in the mainland (Miranda *et al.*, 2006; http://portaldoclima.pt/, 2017) that can be of 20%-40% relative to the present values (Miranda *et al.*, 2006) are expected.

In this context, understanding the natural dynamics of estuarine and coastal ecosystems and their response to changes in the human-related or climatic drivers is fundamental to guarantee their environmental quality.

3. Tagus Estuary

3.1 General overview

The Tagus estuary, located in the Portuguese west coast, is one of the largest estuaries in Europe with an area of about 320 km^2 (APA, 2016). This mesotidal coastal plain estuary has a complex morphology (Figure 3.1) with a deep, long and narrow inlet connecting the Atlantic Ocean to a broad and shallow inner basin that has extensive tidal flats and marshes. About 40 km upstream, the estuary markedly narrows at the bay head. The intertidal area represents about 43% of the total estuarine surface (Castanheiro, 1986).

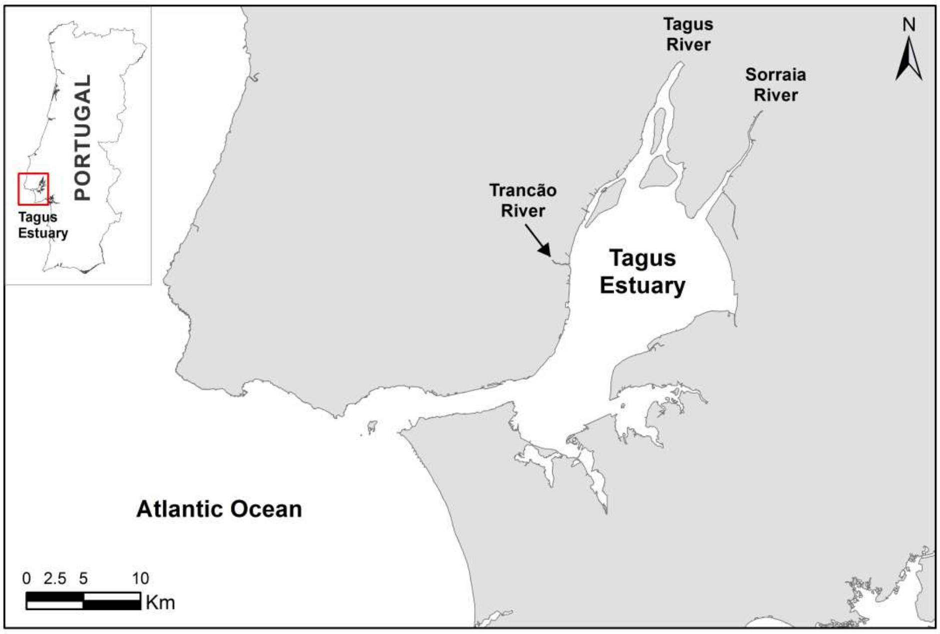
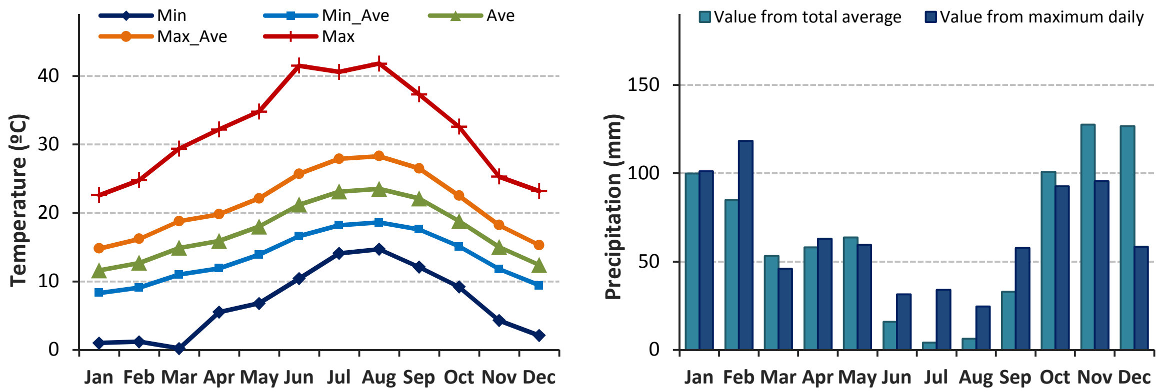


Figure 3.1. General overview of the Tagus estuary.
Source: Portuguese coastline, Instituto Hidrográfico.

The estuary is part of the transnational Tagus river basin that covers an area of about 80800 km^2, of which about 31% is located in Portugal (APA, 2016). The Tagus River itself is about 1100 km long (230 km in Portugal). In Portugal the main tributaries of the Tagus basin are the Zêzere River in the right margin, with a basin of 4980 km^2, and the Sorraia River in the left margin, with a basin of 7520 km^2, which together represent 50% of the Tagus basin area in Portugal (APA, 2016). The longitudinal east-to-west development of the Tagus basin stands as a climatic divide between the rainy northern Iberian territory and the southern dry part, which is well represented in the differences between the Zêzere and Sorraia basins (Alphen *et al.*, 2016). In the southern part of the basin, and in particular in the Lisbon region where the Tagus estuary is located, the climate is temperate with dry summers (IPMA, https://www.ipma.pt/en/oclima/normais.clima/, January 2017). The average temperature in Lisbon is about 22 ºC in summer, while in winter it decreases to 12 ºC (Figure 3.2). Summers are usually dry and the average rainfall in autumn and winter ranges from 80 mm to 125 mm (Figure 3.2).



Legend: Min - lowest minimum temperature value; Min_Ave - average from minimum temperatures; Ave - Average from average temperatures; Max_ave - average from maximum temperatures; Max - highest maximum temperature.

Figure 3.2. Temperature and precipitation climate normals in Lisbon between 1981-2010. Data source: IPMA, https://www.ipma.pt/en/oclima/normais.clima/, January 2017.

The area surrounding the Tagus estuary is intensively occupied and the estuarine margins support diverse uses and activities, such as urban, industrial/harbors, agriculture, shellfish harvesting. The estuary is included in the Metropolitan Area of Lisbon and comprises along its margins 11 municipalities with about 1.6 million of total inhabitants. The western and northern margins of the estuary are densely urbanized, contrasting with the productive agricultural areas along the eastern side (Tavares *et al.*, 2015; Figure 3.3). The detailed land use cartography of the estuarine fringe[1], that covers a total area of 130 km^2 in the Tagus estuary, shows the following occupation along its margins (Rilo *et al.*, 2012): agricultural areas (35%), urban zones (34%), industrial, port and airport facilities (24%), green spaces (i.e. areas with vegetation in urban and non-urban zones, gardens, and leisure facilities, 6%) and natural areas (i.e. regions that still preserve their natural characteristics, 1%). In the intertidal area, occupation includes (Rilo *et al.*, 2012): salt marshes (13%), anthropogenic structures (e.g. salt pans, old tide mills or aquaculture installations, 15%) and beaches (1%). Human activities in the intertidal zones and along the estuarine margins are identified as the main driver for the loss of natural areas and estuarine shoreline changes during the last 60 years (Rilo *et al.*, 2012). Part of the

[1] The estuarine fringe is defined by the Portuguese law as the 550 m wide fringe above the water line at the highest astronomical tide.

estuary is classified as sensitive area[2], excluding the nutrient criteria, due to *Escherichia coli* concentrations (APA, 2012b).

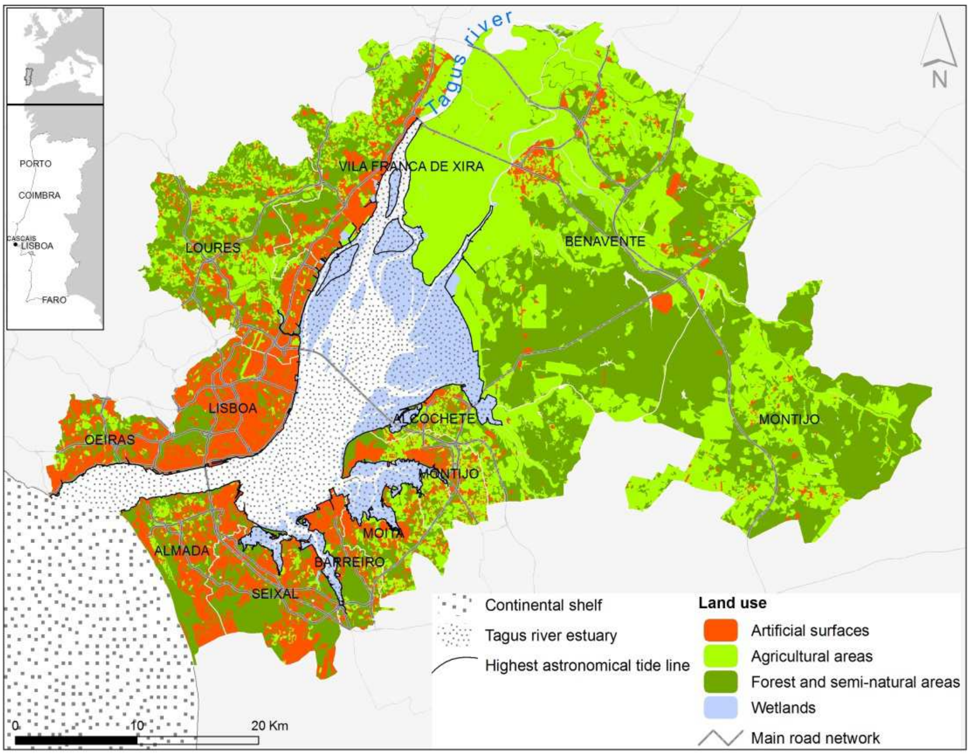


Figure 3.3. Occupation along the Tagus estuary margins (Tavares *et al.*, 2015).

The ecological and natural values of the Tagus estuary, associated with both the wetlands and the terrestrial habitats and the biological diversity, are well recognized. The Tagus estuary hosts a natural reserve, the Tagus Estuary Natural Reserve[3] (Figure 3.4), covering about 14000 hectares, which is one of the most important sanctuaries for wintering or staging birds in Europe and also an important nursery area for fish and shellfish juveniles. The middle-upstream area of the estuary is also classified under the Birds and Habitats Directives as, respectively, Special Protection Area (PTZPE0010, Estuário do Tejo, about 44800 ha) and a Site of Community Importance (PTCON0009, Estuário do Tejo, about 44600 ha), and under the Ramsar Convention as a Wetland of International Importance (Figure 3.4).

Morphologically the Tagus estuary can be divided into three regions (Ferreira *et al.*, 2003): i) the upstream section (located between Vila Franca de Xira and the Alcochete-Sacavém section), characterized by low depths (average depth of 2 m), includes most of the mudflats and salt marshes, and also the "Mouchões", the local term for the islands formed by alluvial deposition; ii) the middle

[2] Decree-law 198/98, October 8.

[3] The Tagus Estuary Natural Reserve is classified as a Protected Area (Área Protegida, AP) under the Decree-law n.º 565/76, July 19.

section, with an average depth of 7 m; and iii) the downstream section, which represents the main navigation channel of estuary and can reach depths of 45-50 m. The estuary width varies between about 500 m, in the upstream section, and 15 km, in the inner bay. The bathymetry of the estuary is presented in Figure 3.5.

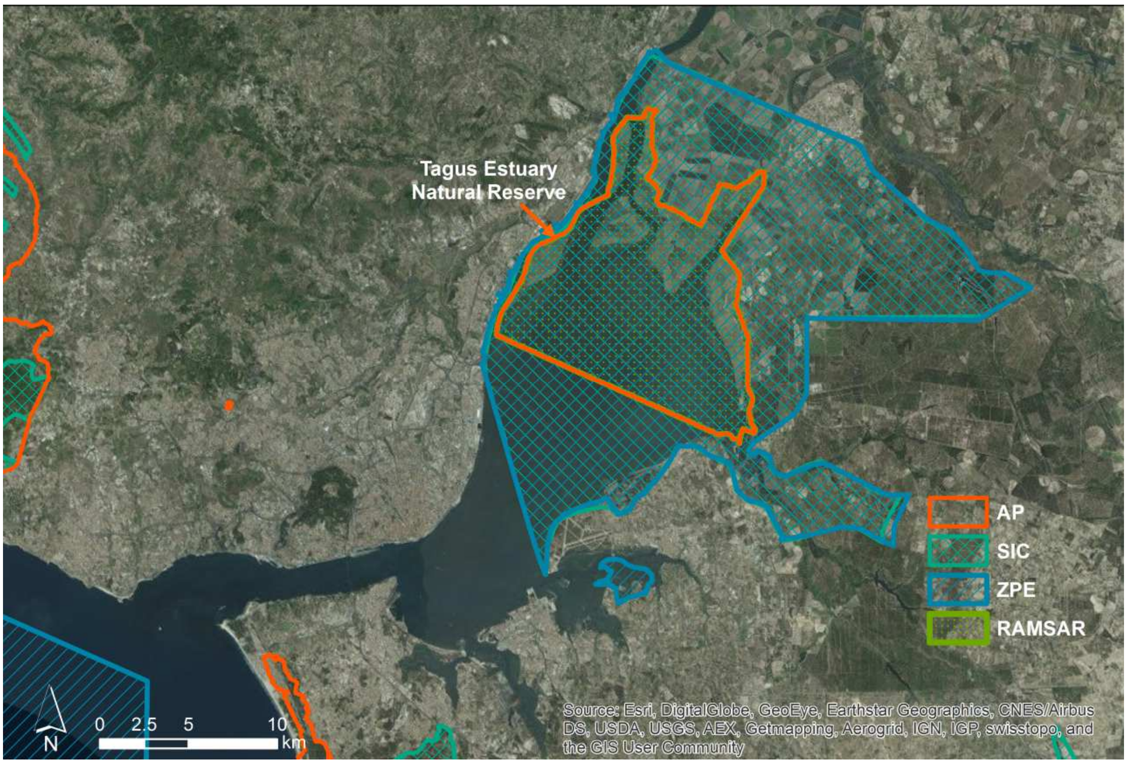


Figure 3.4. Protected areas in the Tagus Estuary: Tagus Estuary Natural Reserve (protected area, AP), Site of Community Importance (SIC), Special Protection Area (ZPE) and RAMSAR site. Data source: ICNF, http://www.icnf.pt, January 2017.

In the context of the Water Framework Directive (WFD), the Tagus estuary is classified as a transitional water[4] of the typology A2 – mesotidal well-mixed estuary with irregular river discharge (Bettencourt *et al.*, 2004). Four water bodies[5] are delimited within the estuary (Ferreira *et al.*, 2005, 2006; Figure 3.6): Tejo-WB1, Tejo-WB2, Tejo-WB3 and Tejo-WB4. Tejo-WB1 (182 km^2) corresponds to the downstream, narrow area of the estuary. Tejo-WB2 (159 km^2) corresponds to the inner bay, with the exception of Cala do Norte that corresponds to Tejo-WB3 (96 km^2). Tejo-WB4 (16.5 km^2) is located in the upstream area of the estuary, in the area more influenced by the freshwater input from the Tagus river. The estuary is bound downstream by coastal waters (CWB-I-4, coastal waters adjacent to the Tagus estuary) and surrounded by several river water bodies (Figure 3.6).

[4] Transitional waters are bodies of surface water in the vicinity of river mouths which are partly saline in character as a result of their proximity to coastal waters but which are substantially influenced by freshwater flows.

[5] Water body: a sub-unit in the river basin (district) to which the environmental objectives of the Water Framework Directive must apply.

Many studies showed the importance of the Tagus estuary in terms of sediments, nutrients, contaminants, plankton and fisheries dynamics and its interaction with the adjacent coastal area (e.g. Caçador *et al.*, 1996; Cabeçadas and Brogueira, 1997; Costa and Cabral, 1999; Cabral *et al.*, 2000; Moita, 2001; Cabeçadas *et al.*, 2004; Brogueira *et al.*, 2007; Gameiro and Brotas, 2010; Valente and Silva, 2009; Caetano *et al.*, 2012).

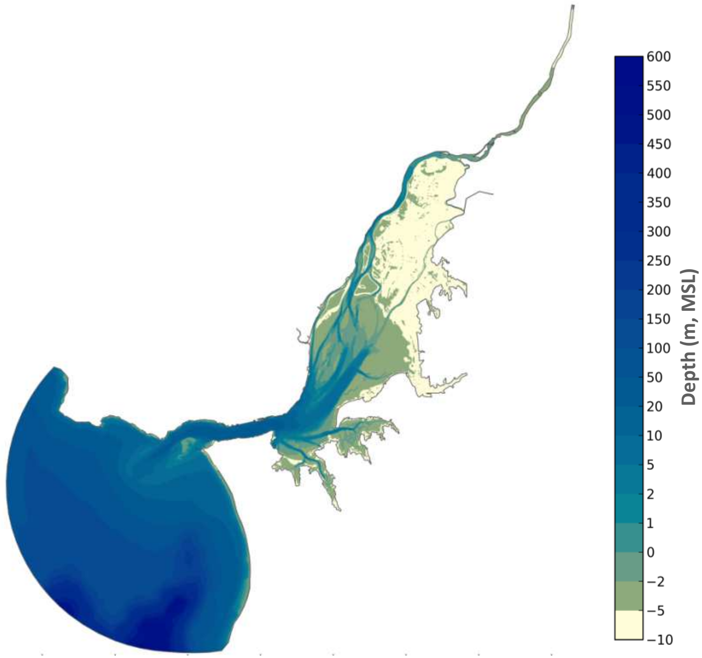


Figure 3.5. Tagus estuary bathymetry (MSL – mean sea level).

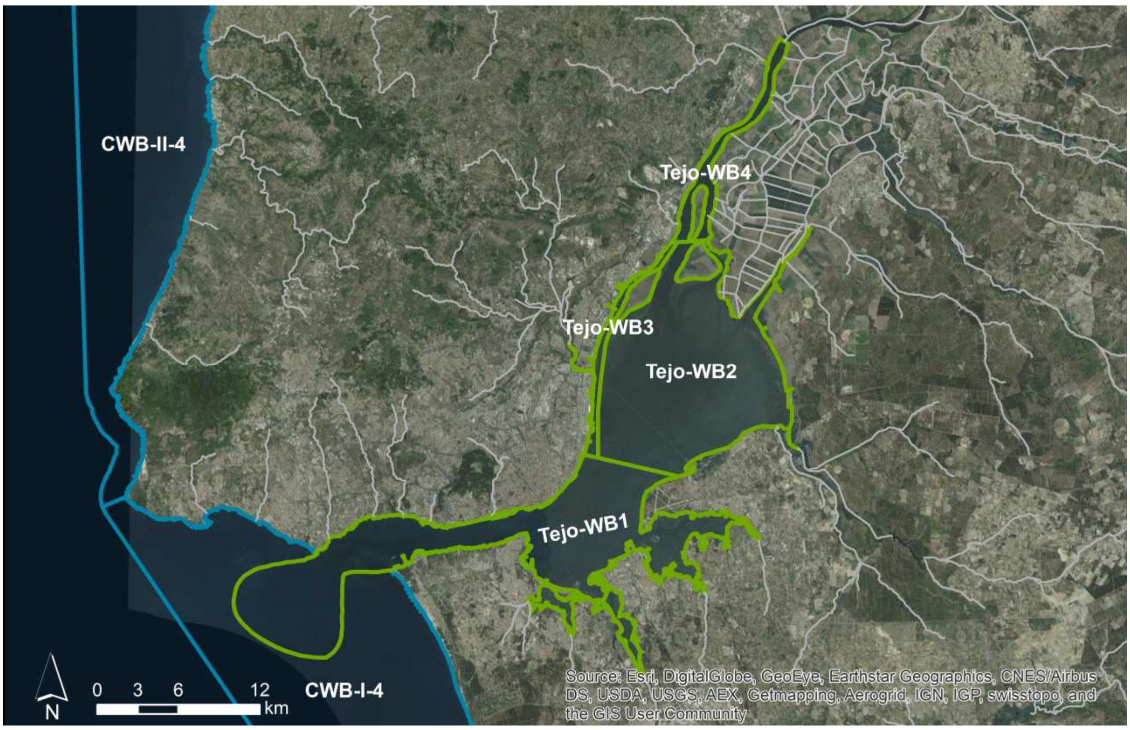


Figure 3.6. Water bodies in the Tagus estuary (green) and adjacent coastal waters (blue), and surrounding river water bodies (grey). Data source: SNIAMB, http://sniamb.apambiente.pt/, December 2016.

3.2 Hydrodynamics

The circulation in the Tagus estuary is primarily driven by tides but it is also influenced by the river flow, wind, atmospheric pressure and surface waves.

Tides are semi-diurnal, as in the whole Portuguese coast. The tidal form number (ratio between the amplitudes of the two major diurnal constituents and the two major semi-diurnal tidal constituents) is close to 0.1 (Table 3.1). Tidal ranges at the nearest coastal gauge (Cascais) vary between 0.55 m and 3.86 m (Guerreiro *et al.*, 2015) but resonance significantly amplifies this range within the estuary (Fortunato *et al.*, 1997, 1999, Figure 3.7). With a resonance period between 8 to 9 hours, the Tagus estuary amplifies the 4th-diurnal and semi-diurnal constituents, while leaving the amplitude of diurnal constituents almost constant (Guerreiro *et al.*, 2015). As a result, the tidal form number decreases along the estuary, reducing the diurnal inequality of the tides (Table 3.1). The estuary is strongly ebb-dominated due to the large extent of the tidal flats (Fortunato *et al.*, 1999). In its middle section, ebbs are shorter than floods by over one hour. In contrast, the upper estuary is slightly flood-dominated (Table 3.1).

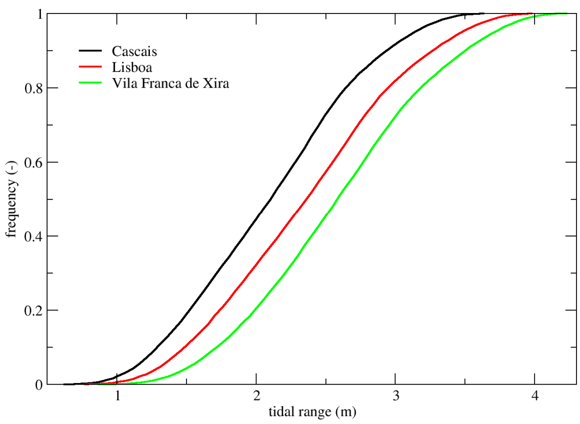


Figure 3.7. Distribution of the tidal ranges along the estuary (from the model of Guerreiro *et al.*, 2015).

Table 3.1. Tidal characteristics along the estuary. The tidal form number is the ratio between the sum of the amplitudes of the two largest diurnal constituents (O_1 and K_1) and the two largest semi-diurnal constituents (M_2 and S_2). Tidal asymmetry is measured by the average difference between ebb and flood durations. Computed from the model of Guerreiro *et al.* (2015).

	Cascais	Lisboa	Vila Franca de Xira
Tidal form number (-)	0.105	0.096	0.093
Tidal asymmetry (min)	-20	-61	11

River discharge may significantly influence water levels, but only farther than 40 km upstream of the mouth (Vargas *et al.*, 2008). Downstream, the water levels are mainly controlled by tides and storm surges. The Tagus river is the main affluent of the Tagus estuary. The mean river discharge is 336 m^3/s (APA, 2012). Other characteristic values are: maximum (10 days/year), 828 m^3/s; median (180 days/year), 239 m^3/s; minimum (355 days/year), 102 m^3/s. Two other rivers contribute significantly to the water inflow to the estuary: the Sorraia River (about 5% of the Tagus River discharge; Rodrigues *et al.*, 2009) and the Trancão River.

The impact of storm surges and waves on the Tagus estuary dynamics is poorly studied. Canas *et al.* (2009) found atmospheric pressure to be more important than wind in determining the surge within the estuary. Oliveira (2000) applied a wave model to the estuary mouth and found that short waves were dissipated in the ebb-delta sand bars at the entrance of the estuary. Rusu *et al.* (2011) analyzed the effect of tidal currents on waves at the Tagus estuary mouth, and found the currents to increase the significant wave height and the mean wave period on ebb and decrease them on flood. Fortunato *et al.* (in review) found that the wave-induced setup can reach tens of centimeters even in the upper reaches of the estuary. Inside the estuary, locally-generated waves can reach significant wave heights of 0.8 m. This value was measured between Cacilhas and Seixal during an extreme event with winds of about 11 m/s (Freire *et al.*, 2009), and simulated by Rusu *et al.* (2009) for winds of 12 m/s.

The estuary is often considered well-mixed, even though stratification has been observed at high flow rates (Neves, 2010, Figure 3.8). Since little is known about the conditions under which the estuary can be stratified, the empirical model of Uncles *et al.* (1983) was used herein to obtain a first estimate on the conditions that can lead to stratification. These authors base their estimate on the ratio Ur/Ut, where the river velocity (Ur*)* is defined as the river discharge divided by the cross-section, and the tidal velocity (Ut*)* is the mean velocity due to tides. The estuary is well mixed for Ur/Ut<0.01, stratified for Ur/Ut>0.1 and partially-mixed otherwise. This ratio was computed using the model of Fortunato *et al.* (1999) for neap, mean and spring tides conditions, and for a range of river flows. Results (Figure 3.9) indicate that the estuary is well-mixed for average and lower river flows, but that it can be partially-mixed for higher river flows, and even stratified for extreme river flows, particularly under neap tide conditions. For river flows lower than 1000 m^3/s, Portela (1996) and Silva (2003) have also estimated that the Tagus estuary is vertically homogeneous. Further investigations are required to better understand the stratification conditions in this estuary.

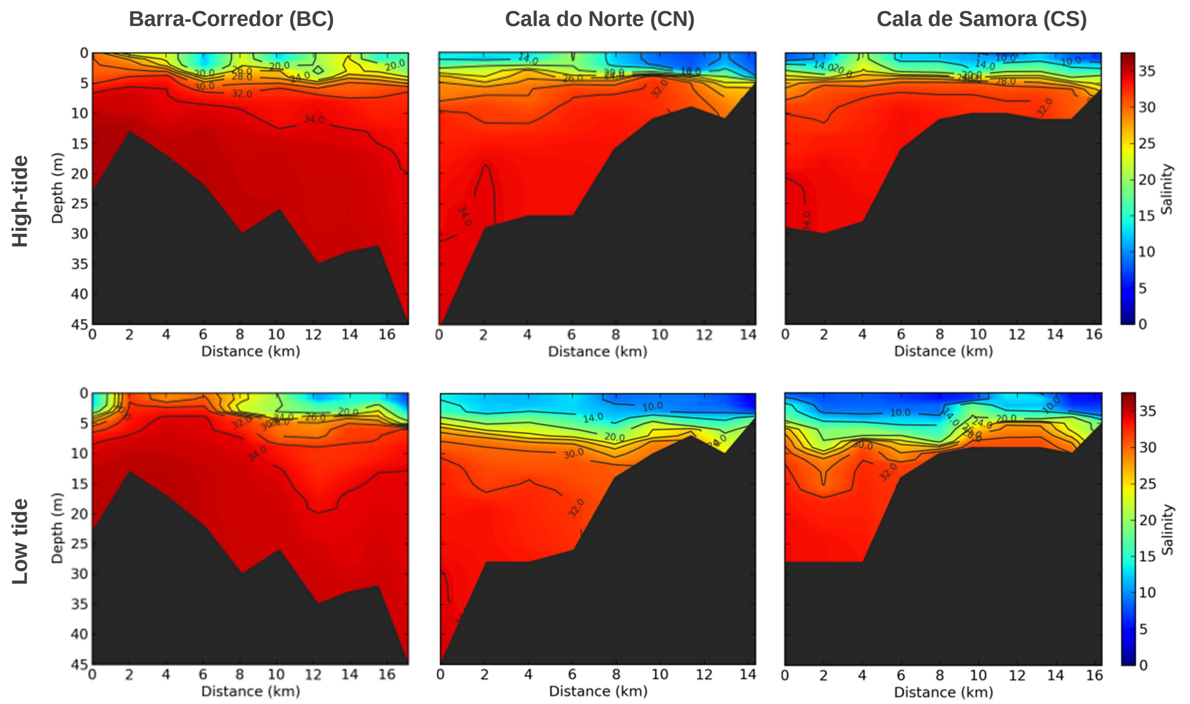


Figure 3.8. Observations of stratification in three profiles in the Tagus estuary (February 11-13, 1988). Adapted from Rodrigues *et al.* (2016).

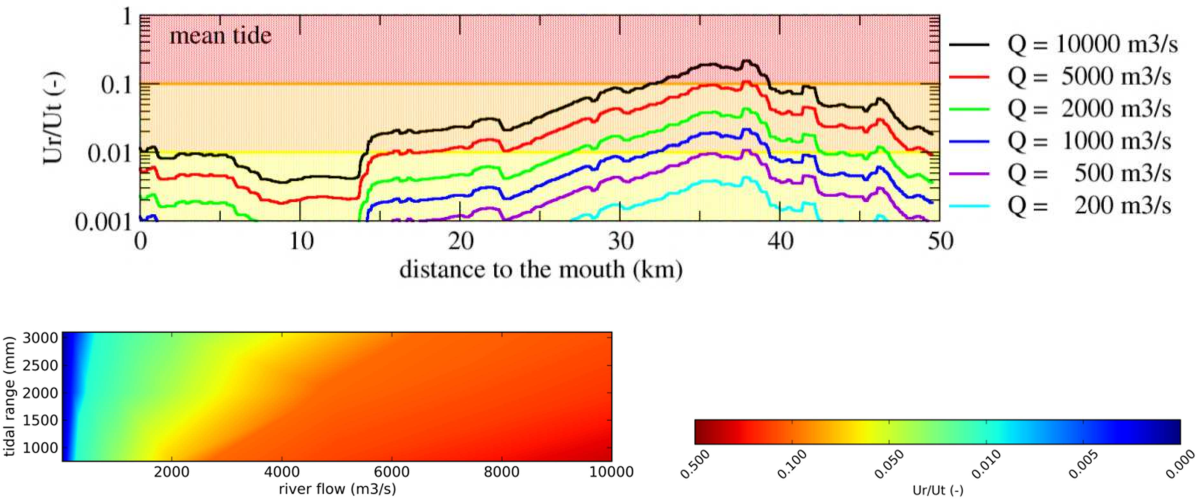


Figure 3.9. Stratification conditions in the Tagus estuary according to the criterion of Uncles *et al.* (1983), using the model of Fortunato *et al.* (1999). The estuary is well-mixed for Ur/Ut<0.01, stratified for Ur/Ut>0.1, and partially mixed otherwise.

Residence times in the Tagus estuary were studied by Oliveira and Baptista (1998) and Braunschweig *et al.* (2003) using depth-averaged barotropic shallow water models. Oliveira and Baptista (1997) found average residence times of the order of 5-20 days for rivers flows of 400-4000 m^3/s. Also, these authors found a significant spatial variability, with higher residence times in lateral bays and in the upper estuary. Braunschweig *et al.* (2003) found slightly higher values (about 7-23 days for a river discharge of 330 m^3/s). These authors also concluded that the effect of wind on residence times was small, although only one wind condition was tested. In contrast, Vaz and Dias (2014) concluded that wind affects residual circulation in the Tagus estuary, and therefore on residence times.

The Tagus estuary has a strong sediment dynamics, driven by tides and waves (Franz *et al.*, 2014). The Tagus River is the main source of sediments, with a mean yearly input estimated at $4x10^5$ tons (Vale and Sundy, 1987). Sediments are generally muddy, except along some channels and margins (Figure 3.10). Sedimentation rates in the salt marshes are of the order of 1-2 cm/year (Silva *et al.*, 2013). In contrast, navigation channels appear to be stable, probably due to dredging (Guerreiro *et al.*, 2015).

In general, much is known about tidal propagation and water levels in the Tagus estuary, both from the analysis of a large tide gauge dataset from 1972 and from the application of several numerical models. In contrast, the present knowledge of estuarine circulation, salinity dynamics and low-frequency motions in this estuary must be extended. Detailed datasets on salinity during stratification events (e.g. Neves, 2010) are still scarce and developments towards a more accurate three-dimensional baroclinic numerical model of the estuary are still recent (Rodrigues *et al.*, 2016).

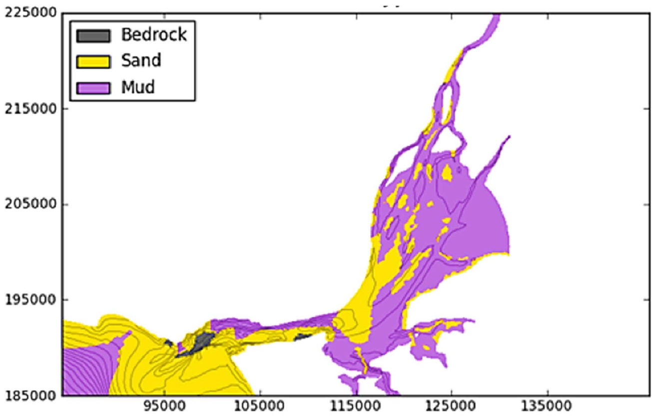


Figure 3.10. Bottom sediment types in the Tagus estuary (prepared by F. Ganthy based on data from Freire, 2003).

3.3 Biogeochemical dynamics and water quality

Several environmental studies based on observations have been carried out in the Tagus estuary (e.g. Martins *et al.*, 1982, 1983; Silva *et al.*, 1986; Brogueira and Cabeçadas, 2006; Gameiro *et al.*, 2007; Valença *et al.*, 2011; Caetano *et al.*, 2016), providing important historical data to understand the Tagus estuary biogeochemical and water quality dynamics.

Although most of the data tends to be scattered, there are some studies of broader spatial or temporal coverage (Figure 3.11). The "Estudo Ambiental do Estuário do Tejo" (EAET) was carried out in the early 1980s, between 1980 and 1983, and is one of the most complete quasi-synoptic datasets of water quality in the Tagus estuary (Martins *et al.*, 1982, 1983; Silva *et al.*, 1986). Another important monitoring program, the "Vigilância da Qualidade do Meio Marinho" (VQM) project, was developed by the Instituto Hidrográfico and covered the entire area of the estuary, during its first phase from 1981 until 2010 (Palma *et al.*, 2000; Valença *et al.*, 2011, http://www.hidrografico.pt/vqm.php, February 2017). In the middle and upstream areas of the estuary a monitoring program (FCUL-VALORSUL) is also being undertaken since 1999 (Gameiro *et al.*, 2007; Gameiro and Brotas, 2010; Brotas, unpublished data), which constitutes one of the few ongoing monitoring programs in the estuary. A monitoring program of broader spatial coverage was also established along the estuary, between 1999/2001 and 2004 (Brogueira and Cabeçadas, 2006; Brogueira *et al.*; 2007). More recently (2009-2010) some specific field campaigns covering the entire estuary were performed to support the implementation of the WFD (Brito *et al.*, 2012a; Caetano *et al.*, 2016) and two online water quality buoys were installed in the estuary in the scope of the ENVITEJO project (https://www.apambiente.pt/index.php?ref=x76, February 2017). Annex I presents a non-exhaustive summary of the most relevant environmental data collected in the Tagus estuary since the 1960s.

Taking into account the results of these studies, the main spatial and temporal patterns of the relevant physical, chemical and biological variables in the scope of this project are characterized. These variables include dissolved oxygen, nutrients and chlorophyll *a* (commonly used as a proxy for phytoplankton biomass; e.g. Brito *et al.*, 2015), and other physical and chemical variables that characterize the water matrix (e.g., salinity, water temperature, pH).

Salinity, water temperature, pH and dissolved oxygen

Salinity presents a marked seasonal pattern and a spatial gradient, both characteristics of estuaries, (e.g. Valença *et al.*, 2011; Martins *et al.*, 1982, 1983; Silva *et al.*, 1986), and dependent on the combined role of the river flow and the tides. Between 1985 and 2009 salinity ranged from <2 upstream to 36.9 downstream (Valença *et al.*, 2011). Some higher values were found by Martins *et al.* (1982), with an average salinity downstream of 35.5 (1980-1983) (Martins *et al.*, 1982, 1983; Silva *et al.*, 1986). Water temperature also presents a seasonal variation, the larger temperatures occurring during summer, as expected (e.g. Silva *et al.*, 1986; Gameiro *et al.*, 2007). Maximum values of approximately 24-27 ºC are observed from June to August in the shallower upstream areas, and minimum values of approximately 9-10° C are observed in December–January (Martins *et al.*, 1982, 1983; Silva *et al.*, 1986; Gameiro *et al.*, 2007; Brito *et al.*, 2015). No significant changes were found in the water temperature from three distinct periods (1960s, 1980s and 1999-2010) in the middle-upper estuary (Brito *et al.*, 2015). Figure 3.12 presents the observed mean salinity and water temperature along the Tagus estuary between 1980 and 1983.

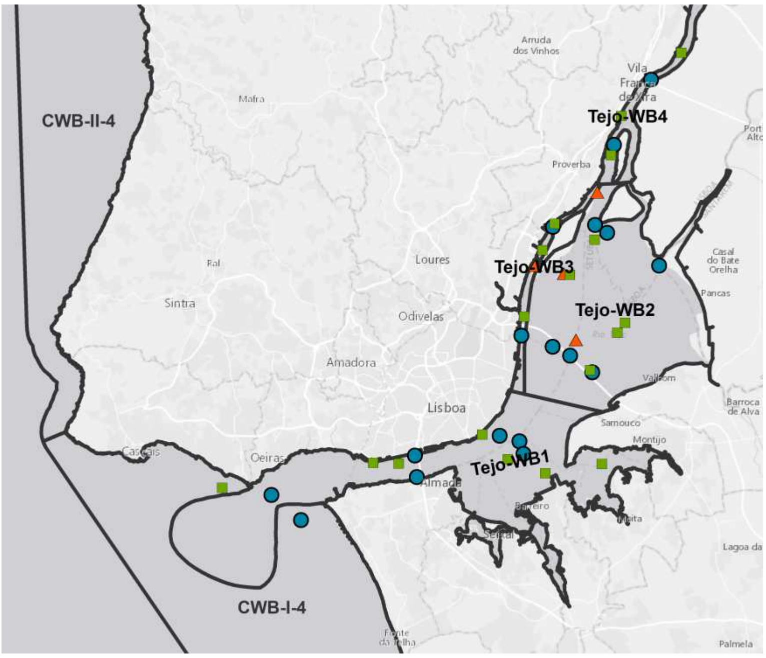


Figure 3.11. Location of the sampling stations of some of the most relevant environmental studies in the Tagus estuary (blue circles: Martins *et al.*,1982, Martins *et al.*, 1983, Silva *et al.*, 1986; green squares: Ferreira and Vale, 2010, Brito *et al.*, 2012a, Caetano *et al.*, 2016); orange triangles: Gameiro *et al.*, 2007, Gameiro and Brotas, 2010, Brotas, unpublished data). Background image from ESRI.

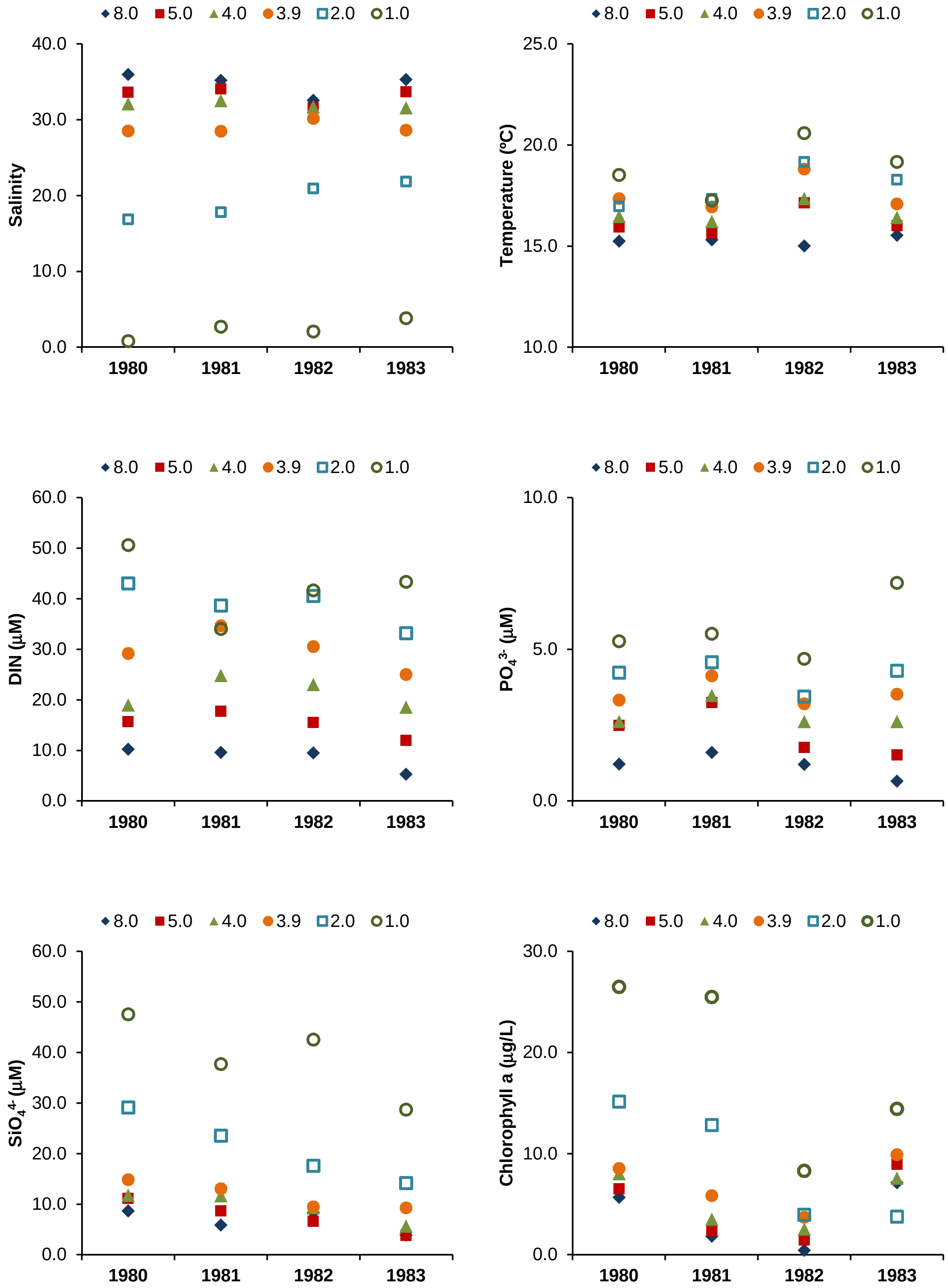


Figure 3.12. Mean salinity, water temperature, dissolved inorganic nitrogen (DIN), phosphate (PO_4^{3-}), silicate (SiO_4^{4-}) and chlorophyll *a* along the Tagus estuary between 1980 and 1983. Stations 8.0 to 1.0 are located along the estuary from downstream to upstream. Stations 8.0, 5.0 and 4.0 are located in Tejo-WB1, stations 3.9 and 2.0 are located in Tejo-WB2 and station 1.0 is located in Tejo-WB4. Data source: Martins *et al.*, 1982, 1983; Silva *et al.*, 1986.

Regarding pH, a typical seasonal variation was found in the Tagus estuary, with lower values occurring after winter due to the larger river flows (Valença *et al.*, 2011). Observed mean pH is about 8 (Martins *et al.*, 1982, 1983; Silva *et al.*, 1986; Caetano *et al.*, 2016), ranging typically between 7.5 and 9 (Valença *et al.*, 2011). However, some lower values, down to 5, were also observed (Martins *et al.*, 1982; Gameiro *et al.*, 2007; Brotas, unpublished data). The larger variability occurs in the areas with a stronger fluvial influence (Valença *et al.*, 2011). No significant pH variations were found between 1985 and 2009 (Valença *et al.*, 2011).

Observed mean dissolved oxygen concentrations in the Tagus estuary are about 8 mg/L (Martins *et al.*, 1982, 1983; Silva *et al.*, 1986; Caetano *et al.*, 2016). Hypoxia episodes, characterized by concentrations lower than 3 mg/L (Nezlin *et al.*, 2009), were not observed in the available datasets. Considering 80% as the reference value for the percent saturation of dissolved oxygen as good indicator of the trophic status of estuarine waters (Valença *et al.*, 2011), some concentrations below this threshold were observed both in the 1980s and more recently (Figure 3.13). Episodic concentrations below 40% were observed by Valença *et al.* (2011). The lower dissolved oxygen concentrations tend to occur in the areas of larger anthropogenic influence (Valença *et al.*, 2011).

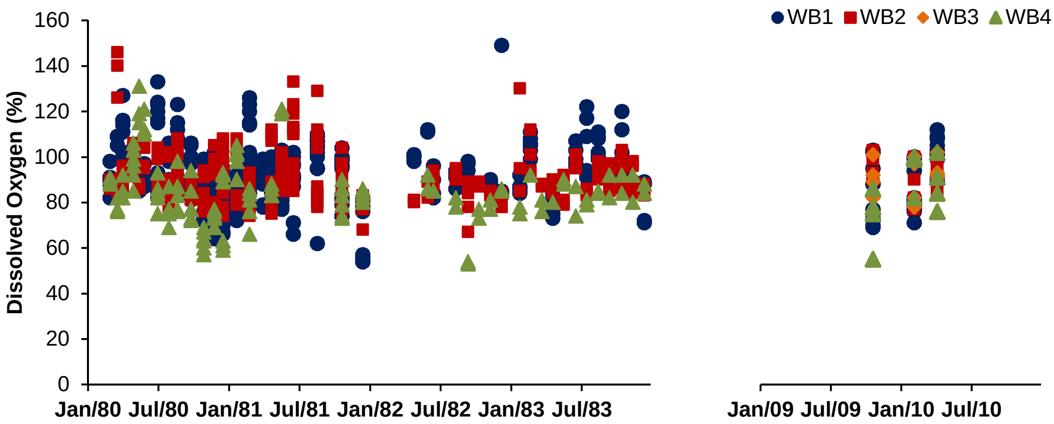


Figure 3.13. Dissolved oxygen in the water bodies of the Tagus estuary during the 1980s (Martins *et al.*, 1982, 1983; Silva *et al.*, 1986) and the 2009-2010 (Caetano *et al.*, 2016) field campaigns.

Nutrients

Nutrients present, typically, a marked spatial gradient with higher concentrations upstream, in the areas more influenced by the freshwater discharges (e.g. Valença *et al.*, 2011; Martins *et al.*, 1982, 1983; Silva *et al.*, 1986; Caetano *et al.*, 2016; Figure 3.12). Higher nutrients concentrations were also associated with the proximity of urban areas, influenced by the discharges of urban and industrial effluents (Valença *et al.*, 2011). The extension of the horizontal gradients tends to change seasonally: the river-influenced, nutrient-enriched zone (upper estuary) extends downstream during high river flows, while the more saline, nutrient-impoverished zone (lower-middle estuary) extends upstream under low river flows (Brogueira and Cabeçadas, 2006). Nutrient concentrations tend to show broader differences between upper and lower estuary in autumn and winter (Caetano *et al.*, 2016).

Nutrients concentrations observed in the Tagus estuary over different periods are presented in Table 3.2. Ammonium ranged from 0.03 to about 120 µM and nitrate + nitrite ranged from 0.2 to about 520 µM (Table 3.2), the larger concentrations being observed in the upstream area. Silicate also presented a wider range, between 0.3 and about 260 µM (Table 3.2), with larger concentrations upstream. Phosphate ranged from 0.1 to about 19 µM (Table 3.2). Nutrient ranges found by Caetano *et al.* (2016) tend to be lower than those observed on other studies, which is explained by the sampling approach used in that study that aimed to characterize average conditions. Median concentrations of inorganic nutrients in the Tagus estuary tend to be two to three times higher than in other Portuguese estuaries (Caetano *et al.*, 2016). Valença *et al.* (2011) suggested that significant variations occurred in nitrogen and phosphorous concentrations in the Tagus estuary between 1985 and 2009.

Table 3.2. Observed mean concentrations and ranges (in parentheses) of nutrients and chlorophyll *a* (Chla) in the Tagus estuary.

Period	NH_4^+ (µM)	NO_3^-+NO_2^- (µM)	DIN (µM)	PO_4^{3-} (µM)	SiO_2 (µM)	Chla (µg/L)	Reference
1980-1983	8.9 (0.2-78.0)	21.2 (1.0-520.8)	30.1 (1.5-525.7)	3.5 (0.1-11.3)	18.0 (0.3-178.1)	8.8 (0.1-88.0)	Martins *et al.* (1982) Martins *et al.* (1983) Silva *et al.* (1986)
2001-2004[a]	4.2-11.5	33.4-89.1	45-93	2.3-3.7	35-116	0.6-4.2	Brogueira and Cabeçadas (2006)
2009-2010	8.4 (0.7-46.5)	32.6 (2.5-87.6)	41.1 (3.8-92.5)	2.4 (0.3-7.5)	38.0 (4.8-124.2)	1.4 (0.2-4.9)[b]	Ferreira and Vale (2010) Caetano *et al.* (2016) Brito *et al.* (2012a) www.apambiente.pt, 2016
1999-2015[c]	13.2 (0.03-118.7)	44.9 (0.2-398.7)	58.3 (0.8-402.2)	3.7 (0.8-19.1)	51.1 (1.2-258.4)	3.8 (0.03-32.3)	Gameiro *et al.* (2007) Gameiro and Brotas (2010) Brotas (unpublished data)

[a] Range of the average values.

[b] Data from the October 2009 and April 2010 field campaigns. Brito *et al.* (2012) estimates the following average concentrations: i) considering all the EEMA field campaigns, 2.7 µg/L (salinity ≤ 5), 0.8 µg/L (salinity >5 and ≤25) and 1.0 µg/L (salinity > 25); and ii) considering an historical dataset from 1992-2010, 4.1 µg/L (salinity ≤ 5), 4.4 µg/L (salinity >5 and ≤25) and 4.6 µg/L (salinity > 25).

[c] Data from stations located in the middle-upstream area of the estuary.

Caetano *et al.* (2016) established a methodology to classify the Portuguese transitional waters regarding the chemical status of nutrients, which defines nutrient benchmark values based on the 90th percentile of nutrients data collected in 12 estuaries (Table 3.3). Based on this methodology, a "Low" nutrient quality status was proposed for the Tagus estuary (Caetano *et al.*, 2016). This classification was due to the phosphate concentrations in the upstream estuary (TE-WB4; Table 3.4), which significantly exceeded the proposed benchmark. The downstream area of the estuary (TE-WB1) was classified as "High" quality and the middle estuary (TE-WB2 and TE-WB1) was identified to be at risk, due to relatively high concentrations of both phosphorus and nitrogen (Table 3.4). Applying the proposed methodology to the 1980-1983 and 1999-2015 datasets a “Low” quality score is also obtained (Table 3.4), suggesting that high loads of nutrients have been reaching the estuary over time. The “Medium-Low” classification observed throughout the estuary during the 1980s was mainly due to high phosphate concentrations, while during the 1999-2015 period both inorganic nitrogen and phosphate exceed the benchmark values in the middle-upstream area of the estuary.

Table 3.3. Nutrients benchmark values proposed by Caetano *et al*. (2016) for the Portuguese transitional waters.

Nutrient	Salinity: < 1	Salinity: 1-35
NH_4^+ (µM)	18	18
NO_3^- + NO_2^- (µM)	89	47
PO_4^{3-} (µM)	2.8	3.4

Table 3.4. Classification of the chemical status of nutrients in the Tagus estuary water bodies based on the methodology by Caetano *et al.* (2016): comparison between datasets from three distinct periods. The parameters responsible for the classification are H (High, green), M (Medium, yellow) and L (Low, red) and the colors are attributed by the worst classification. The nutrients responsible for the classification are identified in parentheses.

	TE-WB1	TE-WB2	TE-WB3	TE-WB4
1980-1983	M (PO_4^{3-})	M (PO_4^{3-})	M (NH_4^+, PO_4^{3-})	L (PO_4^{3-})
2009-2010[a]	H	M (NO_3^-, PO_4^{3-})	M (NH_4^+, NO_3^-, PO_4^{3-})	M (NO_3^-) L (PO_4^{3-})
1997-2015		M (NH_4^+,NO_3^-, PO_4^{3-})	M (NO_3^-, PO_4^{3-}) L (NH_4^+)	

[a] From Caetano *et al.* (2016).

Nutrient-salinity relationships, which are often used to analyze the physical mixing *versus* nutrient consumption and inputs (e.g. Caetano *et al.*, 2016), have been observed in the Tagus estuary for nitrate, phosphate and silicate (Cabrita and Moita, 1995; Valença *et al.*, 2011; Caetano *et al.*, 2016). Positive correlations have also been found between climatic drivers (rainfall and river flow) and both nitrate + nitrite and silicate, suggesting that the adjacent rivers are the main sources of these nutrients to the estuary (Gameiro *et al.*, 2007). The larger downstream concentrations of nitrate + nitrite occurred during intense rainfall periods (e.g. March 2001; Brogueira and Cabeçadas, 2006), highlighting the role of the freshwater discharge in controlling their downstream transport. Regarding ammonium and phosphate, sediments resuspension is the most probable source for their renovation in the estuary (Gameiro *et al.*, 2007; Brotas and Gameiro, 2009). The resuspension of salt marshes sediments by tidal flows and the higher temperatures in summer were identified as important drivers in the exchange of ammonium and phosphate between the sediments and the water column in intertidal areas (Cabrita *et al.*, 1999b; Caetano *et al.*, 1997, 2012).

Nutrient enrichment related with human disturbances is often assumed as one of the main causes of cultural eutrophication in estuaries (e.g. Cloern, 2001). In the Tagus estuary nutrients concentrations are typically above the half-saturation constants reported for estuarine phytoplankton: 2 µM for DIN, 0.5 µM for phosphate and 5 µM for silicate (Fisher *et al.*, 1988). In the available datasets, DIN and phosphate concentrations below the respective half-saturation constants occurred in only about 1% of the samples, while concentrations below the silicate half-saturation constant were observed in about 10% of the samples. Brotas and Gameiro (2009) suggested that the inorganic nutrients are not a limiting factor for phytoplankton growth in the Tagus estuary. Nitrogen and phosphorus terrestrial loads transported from the Tagus estuary to the adjacent coastal area have a significant impact on the biological productivity of this zone (Cabeçadas *et al.*, 2004).

Nutrients molar ratios (Figure 3.14) are also often used as indicators to estimate potential nutrient limitation to phytoplankton growth (e.g. Gameiro *et al.*, 2007), the Redfield ratio being the most commonly used (C:Si:N:P = 106:15:16:1; Redfield, 1958; Brzezinski, 1985). Regarding the DIN/P and DIN/Si ratios, seasonal and spatial patterns have been identified in the Tagus estuary (Gameiro *et al.*, 2007). DIN/P ratios are often below 16 in summer (Figure 3.14), suggesting a potential nitrogen limitation (Valença *et al.*, 2011). These low ratios have been related with the larger influence of urban discharges into the Tagus estuary, providing an increase of the phosphorus loads (Valença *et al.*, 2011). The DIN/Si ratios are often above 1 (Figure 3.14).

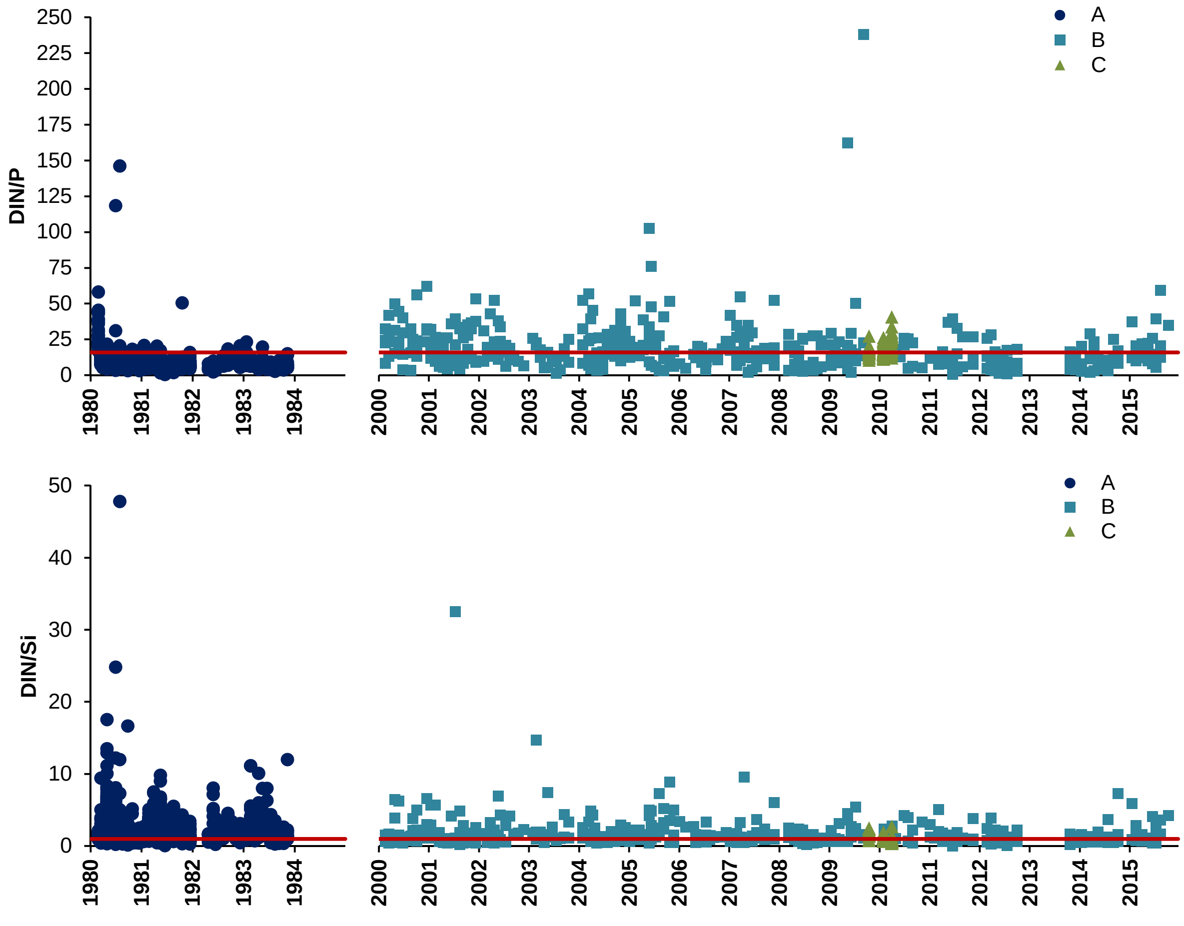


Figure 3.14. Nutrient ratios (DIN/P and DIN/Si) in the Tagus estuary between 1980-1981 (A, Martins *et al.*, 1982, 1983; Silva *et al.*, 1986), 2000-2015 (B, Gameiro *et al.*, 2007; Brotas, unpublished data) and 2009-2010 (C, Caetano *et al.*, 2016). Note that the B dataset derives from data collected only in the middle-upper estuary, while the A and C datasets cover the entire estuary.

Chlorophyll *a*

Chlorophyll *a* presents a marked seasonal pattern, with maximum concentrations around June-July and minimum concentrations mainly in autumn and winter (Gameiro *et al.*, 2007; Brotas and Gameiro, 2009; e.g. Figure 3.15). A clear spatial gradient is also observed with a decrease of chlorophyll *a* from upstream to downstream (e.g. Martins *et al.*, 1982, 1983; Silva *et al.*, 1986; Figure 3.12). Observed mean chlorophyll *a* concentrations over distinct periods are presented in Table 3.2 and available data suggest that chlorophyll *a* concentrations varied throughout the years. In the middle estuary annual mean concentrations tend to be lower in recent years (Figure 3.15), when compared to historical data: 3.4 µg/L in the 2000s, 7.1 µg/L in the 1980s and 7.4 µg/L in the 1960s (Brito *et al.*, 2015). Some episodes with chlorophyll *a* concentrations larger than 10 µg/L, that may be associated with blooms (Gameiro *et al.*, 2007), occurred mainly in the upstream area of the estuary.

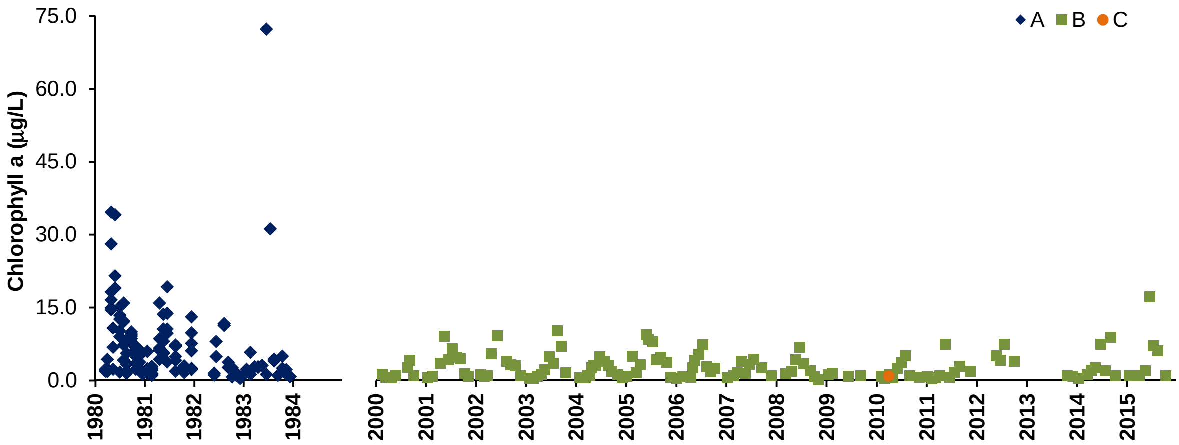


Figure 3.15. Chlorophyll *a* concentrations in the middle Tagus estuary (Tejo-WB3) between 1980-1981 (A, Martins *et al.*, 1982, 1983; Silva *et al.*, 1986, at station 3.9), 2000-2015 (B, Gameiro *et al.*, 2007; Brotas, unpublished data, at station 4) and 2009-2010 (C, Caetano *et al.*, 2016, at station 4).

Significant relationships between chlorophyll *a* and DIN have been found in the Tagus estuary (February and April, 2010; Brito *et al.*, 2012a), with a decrease of nutrients concentrations in spring and summer possibly associated with the phytoplankton consumption (Caetano *et al.*, 2016). Inorganic nutrients are not, however, considered a limiting factor for phytoplankton growth in the Tagus estuary, as mentioned above. Light is often considered as the main limiting factor for phytoplankton growth in the Tagus estuary (INAG, 2002; Gameiro and Brotas, 2010), although the suspended sediments may limit the phytoplankton growth in an intermittent way (Caetano *et al.*, 2016) since their variation is significantly influenced by tide (Vale and Sundby, 1987). Between 1985 and 2009, maximum total suspended solids (TSS) were about 250 mg/L (Valença *et al.*, 2011). Significant relationships have also been found between chlorophyll *a* and air temperature, river flow and PAR – Photosynthetic Active Radiation (Gameiro *et al.*, 2007). Portela (1996) suggested that phytoplankton's interannual variability depends on the environmental conditions and on the upstream phytoplankton concentrations. Residence time has been pointed out as the main factor influencing phytoplankton annual variability (Brotas and Gameiro, 2009): lower chlorophyll *a* concentrations occur during wet years (e.g. 2001), while larger concentrations occur in dry years (e.g. 2005). During very wet periods, the circulation pattern favors the phytoplankton growth near the salt marshes, which tend to accumulate suspended materials and nutrients (Brogueira and Cabeçadas, 2006). Brito *et al.* (2012a) also suggested that phytoplankton growth on estuaries is limited to confined areas.

A shift in the Tagus estuary phytoplankton community from the 1980s to the 2000s has been suggested, with a decrease of the dominance of diatoms and the increase of small cells (e.g. cryptophytes, euglenophytes, prasinophytes) (Brito *et al.*, 2015).

Ferreira *et al.* (2003) assessed the ecological quality of Portuguese transitional and coastal waters using the NEEA approach (Bricker *et al.*, 1999). The Overall Eutrophic Condition (OEC) index was evaluated with primary (e.g. extreme values of chlorophyll concentration) and secondary eutrophication symptoms (e.g. oxygen depletion), while the Overall Human Influence (OHI) index was estimated based on nutrient loads and the susceptibility of systems (e.g. dilution, flushing). Based on this approach the Tagus estuary was classified in “Moderate Low” and “Low” risk regarding the OEC and OHI indexes, respectively. More recently, in the scope of the WFD, Brito *et al.* (2012) proposed a methodology to assess the ecological quality in Portuguese transitional waters, using phytoplankton as a biological indicator and combining both the chlorophyll *a* concentrations (biomass) and single taxa cell elevated counts at the level of species or genus (blooms). All the Tagus estuary water bodies were classified as in “High” or “Good” ecological status. The proposed chlorophyll *a* biomass reference conditions are presented in Table 3.5. For the higher salinities, the proposed values are lower than the ones set for the Portuguese coastal waters (High/Good boundary was set as 8 μg/L and the Good/Moderate boundary as 12 μg/L; Carletti and Heiskanen, 2009; EC, 2008). However, this classification is under revision and lower values are now applied to the central and southern coastal waters (*in* Brito *et al.*, 2012a). Overall, it is considered that the Tagus estuary is not sensitive to eutrophication, fitting into the general classification scheme of lower eutrophication risk estuaries (Ferreira *et al.*, 2003; Gameiro *et al.*, 2007).

Table 3.5. Chlorophyll *a* reference conditions and boundary values proposed by Brito *et al*. (2012a) for the South-wide typology Portuguese transitional waters.

	Chlorophyll *a* (μg/L)		
	Salinity: ≤ 5	Salinity: > 5 - 25	Salinity: > 25
Reference	8	8	6.67
High/Good	12	12	10
Good/Moderate	18	18	15
Moderate/Poor	26.67	26.67	22
Poor/Bad	40	40	33.5

3.4 Pressures

The pressures over the water bodies may be organized in the following groups (APA, 2016):

- Qualitative pressures, which can affect the water quality and can be from point sources (e.g. discharge of urban or industrial effluents) or from diffusive sources (e.g. intensive livestock farming, agriculture);
- Quantitative pressures, which can affect the water availability and are associated with water abstractions (e.g. human consumption, irrigation);
- Hydromorphologic pressures, which can affect the hydrodynamics and are mostly due to changes in the bed and margins of the water bodies (e.g. dredging);
- Biological pressures, which can have direct or indirect impacts on the aquatic ecosystems and have a biological nature (e.g. toxic or invasive species).

Nutrients enrichment and cultural eutrophication are often associated with qualitative pressures on the water bodies (e.g. APA, 2016). In the Tagus estuary, agricultural practices in the adjacent river basins and wastewater discharges are the most important anthropogenic activities regarding the nitrogen and phosphorus inputs into the estuary (APA, 2012a,b). In particular, the main sources of nitrogen and phosphorus discharging into the Tagus estuary are (Ferreira *et al.*, 2003): effluents from domestic and industrial wastewater treatment plants (about 15% of the N load and 40% of the P load), untreated domestic effluents (about 20% of the N load and 15% of the P load), and the Tagus, Sorraia and Trancão rivers, which integrate both diffuse and point loads (about 65% of the N load and 45% of the P load). Since the 1990s, and more effectively since the early 2000s, important investments were made regarding the treatment and disposal of urban effluents from the municipalities bordering the Tagus estuary. Annual nitrogen and phosphorus loads reaching the Tagus estuary are estimated as 14278 ton N per year and 4281 ton P per year, the larger contributor being the Tagus River (Ferreira *et al.*, 2003). Silva (2003) estimated larger loads ranging up to 24030 ton N per year and 7300 ton P per year. Based on 2012 data, the estimated loads of nutrients discharged directly into the estuary from urban wastewater treatment plants are 4250 ton N per year are 686 ton P per year (APA, 2016).

The international nature of the Tagus basin and the modified flow regime along the basin may also affect the water management in the basin and have important cumulative impacts on the downstream water bodies and, in particular, in the estuary (APA, 2016). Several large dams were built in the Tagus River and its tributaries, which reduced the daily average freshwater flow at the Portuguese-Spanish border by about 80 m^3/s, which corresponds to an annual reduction of 27% of the river flow (Rodrigues, 2009). Besides affecting the freshwater flow, these hydromorphological pressures may also affect the nutrients loads and the sediment transport into the estuary (APA, 2016). The harbor infrastructures located along the estuarine margins and the dredging operations for either maintenance or installation of new harbor infrastructures represent also important hydromorphological pressures in the estuary. In 2012 the dredged volume for maintenance in the Tagus estuary was about 380 thousand m^3 (APA, 2016).

The biological pressures in the Tagus estuary are mostly due to the introduction of exotic species, like the Asian clam and the Japanese clam (APA, 2016).

4. Ria Formosa

4.1 General overview

The Ria Formosa, located in the south coast of Portugal (Figure 4.1), is considered the most important coastal ecosystem in the Algarve region. Many valuable goods and services are provided by this coastal lagoon, not only from the social and economic perspectives, integrating several activities (Newton and Mudge, 2003; Newton *et al*., 2014), but also due to its high ecological and environmental values (Barbosa, 2006). The humid area of the lagoon covers about 100 km^2, one third of which corresponds to saltmarshes (Falcão and Vale, 1990), while its watershed covers an area of about 745 km^2 (Ferreira *et al*., 2012). The Ria Formosa is a shallow barrier island system (Barbosa, 2010) that extends along 55 km in the west-east direction with a maximum width of 6 km in north-south direction, depicting a triangular shape (Andrade *et al.*, 2004). The mean depth is 3.5 m, ranging from 6 to 13 m in the main channels (Falcão and Vale, 1990; Barbosa, 2010; Cravo *et al*., 2014).

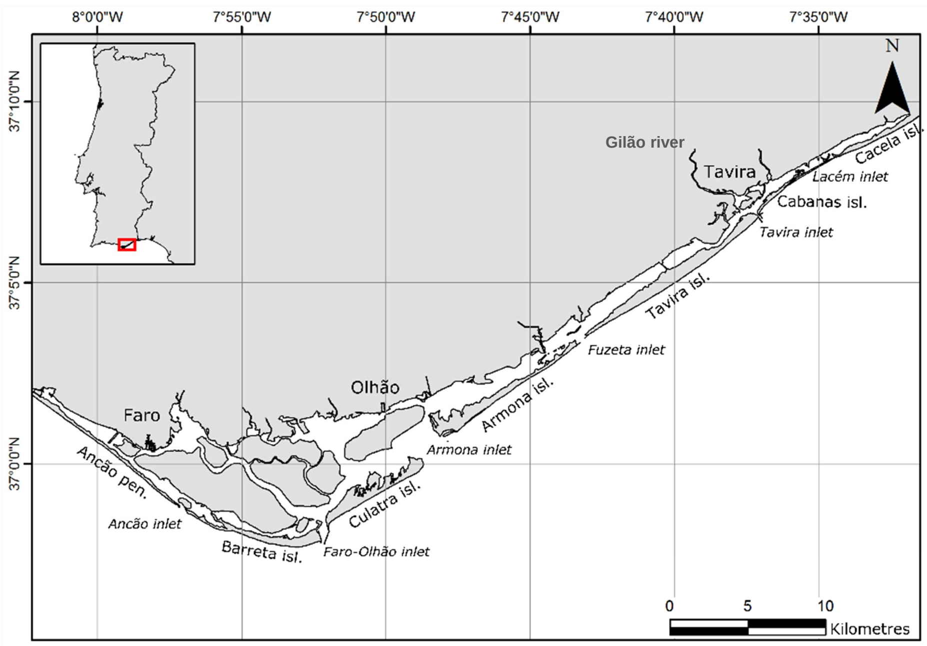
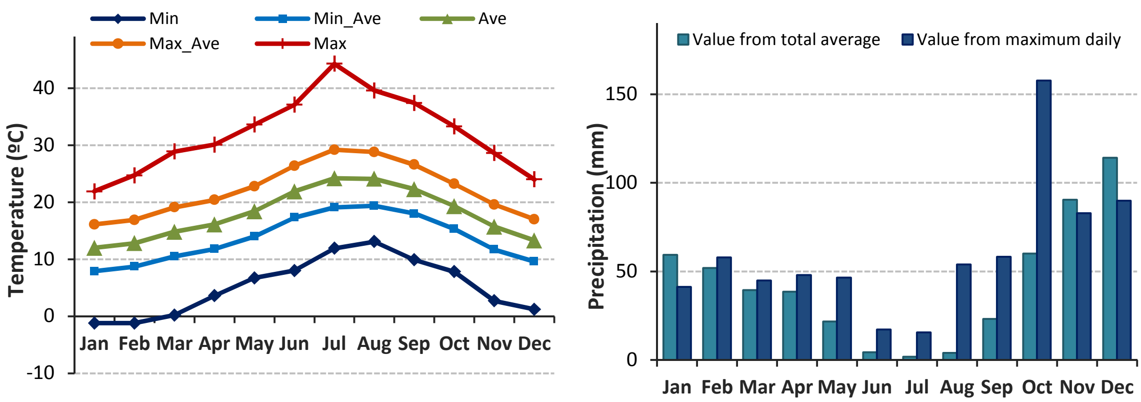


Figure 4.1. Location and general overview of the Ria Formosa lagoon. Source: Esri. Retrieved in January 2016.

The Ria Formosa is a mesotidal lagoon that exhibits very dynamic and complex features. The lagoon is delimited by five sandy barrier islands (Deserta, Culatra, Armona, Tavira and Cabanas) and two peninsulas (Ancão and Cacela), and connects to the Ocean Atlantic through six inlets: Ancão, Faro-

Olhão, Armona, Fuzeta, Tavira and Lacém inlets (Pilkey Jr. *et al*., 1989; Ferreira *et al*., 2003; Figure 4.1). Three sectors (east, central and west, as described in section 4.2) are usually identified. These sectors are linked by a complex network of channels interconnected with the inlets, allowing the recirculation of water within the system and a permanent exchange with the adjacent ocean (Matias *et al*., 2008; Alcântara *et al.*, 2012; Figure 4.1). The most important channels, maintained naturally or partially dredged, allow the navigation to the harbors of the Faro, Olhão and Tavira (Falcão, 1996; Barbosa, 2010; APA, 2012c). These three cities are the major population centres surrounding the Ria Formosa and comprise about 136 thousand inhabitants (INE, 2011).

The Ria Formosa is located on the Atlantic coast, but its climate regime is considered Mediterranean, characterized by dry warm summers and humid and moderate winters (Serpa *et al*., 2005). The average temperature in Faro during the driest summer months (July and August) is about 24 ºC and the minimum of 12 ºC during the winter season (between January and February) (Figure 4.2; IPMA, https://www.ipma.pt/en/oclima/normais.clima/, January 2017). The summer temperature is relatively higher than the mean recorded in Lisbon. The average precipitation occurs mainly between October and February, ranging from 52 to 114 mm (Figure 4.2).



Legend: Min - lowest minimum temperature value; Min_Ave - average from minimum temperatures; Ave - Average from average temperatures; Max_ave - average from maximum temperatures; Max - highest maximum temperature.

Figure 4.2. Temperature (at left) and precipitation (at right) climate normals in Faro between 1981-2010. Data source: IPMA, https://www.ipma.pt/en/oclima/normais.clima/, January 2017.

Industrial activities and the population occupation in the area surrounding the Ria Formosa are much smaller than in the Tagus estuary. The main activities and uses upon this ecosystem include (Figure 4.3): urbanization, livestock, tourism, golf, fisheries, intensive agriculture, aquaculture, industrial development, ports and marinas, sand and salt extraction (50% of the national salt production; Falcão *et al*., 2003) and coastal engineering (artificial inlets) (Newton *et al*., 2014). Agriculture (agricultural heterogeneous areas, agricultural areas with permanent crops) and forests are the predominant land uses in the Ria Formosa basin (Figure 4.3). This basin is mostly influenced by five small rivers and streams (Gilão River, São Lourenço Stream, Seco River, Almargem Stream and Tronco Stream). However, most of them are temporary, totally dry during summer (Newton, 1995; Newton and Mudge, 2003; ICNF, 2008). The Gilão River in Tavira (Figure 4.1), which basin is at least one order of magnitude higher than the remaining rivers and streams (234 km^2; ICNF, 2008), represents the only significant input of freshwater into the system (Newton and Mudge, 2003; Barbosa, 2010). Urban treated effluents, from the surrounding cities, that are discharged into the lagoon (Figure 4.3; Ferreira *et al.*, 2012) represent another source of freshwater besides the natural inputs from superficial waters.

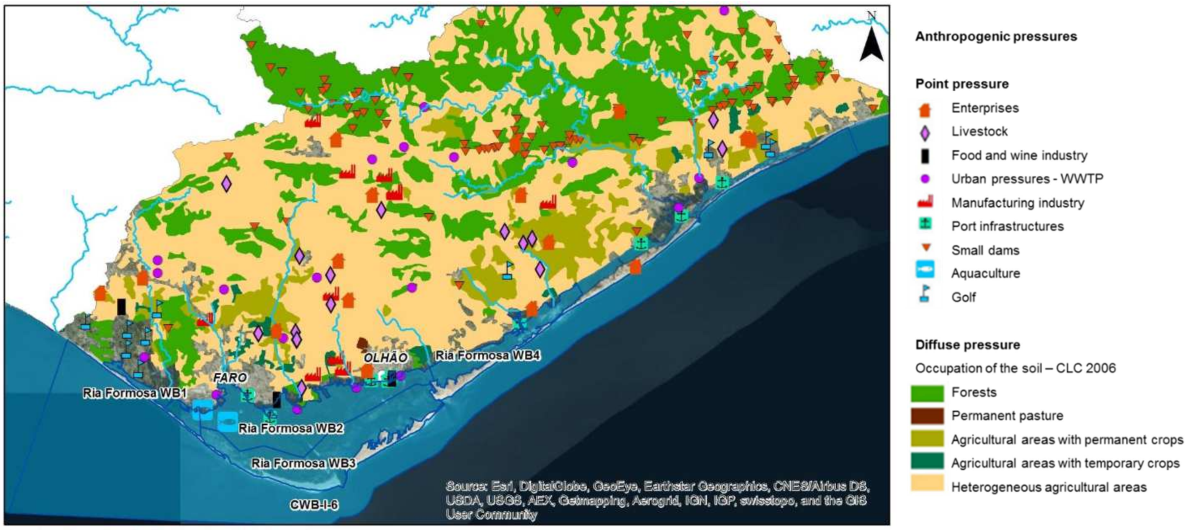


Figure 4.3. Land cover and uses in the Ria Formosa basin. Adapted from: https://www.apambiente.pt/_zdata/Politicas/Agua/PlaneamentoeGestao/PGRH/PGRH_ParticipacaoPublica/PGRH_2/SessoesPublicas/Apresentacao_PGRH8_Faro_5Nov2015.pdf.

The Ria Formosa ecosystem is used for spawning and nursery by many species of fish, crustaceans and bivalves and is recognized as a bird protection and nesting site. From the conservation perspective, the Ria Formosa values are well recognized and protected by legal instruments and directives. In the national context, this coastal lagoon is recognized as a Natural Park since 1987 (about 18400 ha; CCDRA, 2003) and internationally as a Ramsar site (7PT002, 16000 ha; CCDRA, 2003), being part of the Natura 2000 Network. Moreover, the Ria Formosa is included in the list of Special Protection Areas (SPAs, PTZPE0017, 23270 ha) under the Birds Directive (2009/147/EC), in the Sites of Community Importance (SCI, PTCON0013, 17520 ha; CCDRA, 2003) defined by the Habitats Directive (92/43/EEC) and it is also an Important Bird and Biodiversity Areas (IBAs) being valuable for the global bird conservation (Figure 4.4).

In the scope of the WFD, the Ria Formosa is considered a coastal water[6], particularly a mesotidal shallow lagoon (A4 typology; Bettencourt *et al*., 2004), rather than a transitional water. The nutrient load is considered the main driver that can lead to eutrophication in this lagoon (EC, 2000; Newton *et al*., 2003). Additionally, some inner parts of the lagoon are protected under the Nitrate Directive (EEC,

[6] Coastal waters are bodies of surface water on the landward side of a line, every point of which is at a distance of one nautical mile on the seaward side from the nearest point of the baseline from which the breadth of territorial waters is measured, extending, where appropriate up to the outer limit of transitional waters.

1991) and defined as Nitrate Vulnerable Zones (Stigter *et al*., 2006) due to the fertilizer application from the intensive agriculture (Newton & Mudge, 2005).

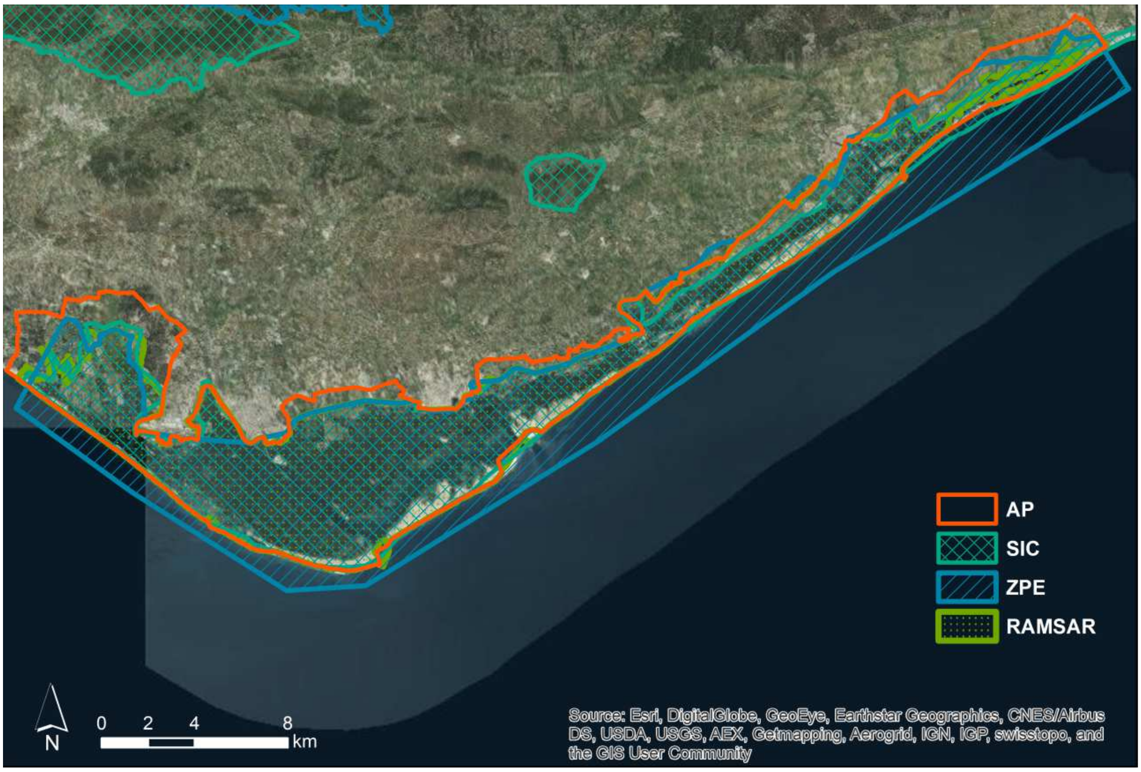


Figure 4.4. Protected areas in the Ria Formosa: Ria Formosa Natural Park (protected area, AP), Site of Community Importance (SIC), Special Protection Area (ZPE) and RAMSAR site (data source: ICNF, http://www.icnf.pt, January 2017).

The Ria Formosa is not homogeneous and within the context of WFD was divided into five water bodies (Figure 4.5). These are affected by distinct circulation patterns and human pressures, which influence the water properties (Ferreira *et al*., 2005, 2006). Ria Formosa-WB1 (4.7 km^2 – APA, 2015) corresponds to the Ancão basin and to the western end of the lagoon. Ria Formosa-WB2 (33 km^2) corresponds not only to the innermost part of the Ria Formosa and to the weaker hydrodynamic regime, but also to the area more influenced by anthropogenic pressures from the Faro and Olhão populations. Ria Formosa-WB3 (30.8 km^2) is characterized by larger exchanges of water through the Faro-Olhão inlet (the major inlet, artificial built in 1929). Ria Formosa-WB4 (10.7 km^2) comprises the Armona and the Fuzeta inlets and is one of the areas with lower anthropogenic pressures (APA, 2012d). Ria Formosa-WB5 (8.8 km^2) corresponds to the area bordered by Tavira and is characterized by lower salinities, justified by the presence of a permanent freshwater source, the Gilão River (Newton and Mudge, 2003). The adjacent coastal water bodies surrounding the Ria Formosa lagoon represent the water bodies CWB-I-6 and CWB-II-7 (APA, 2015).

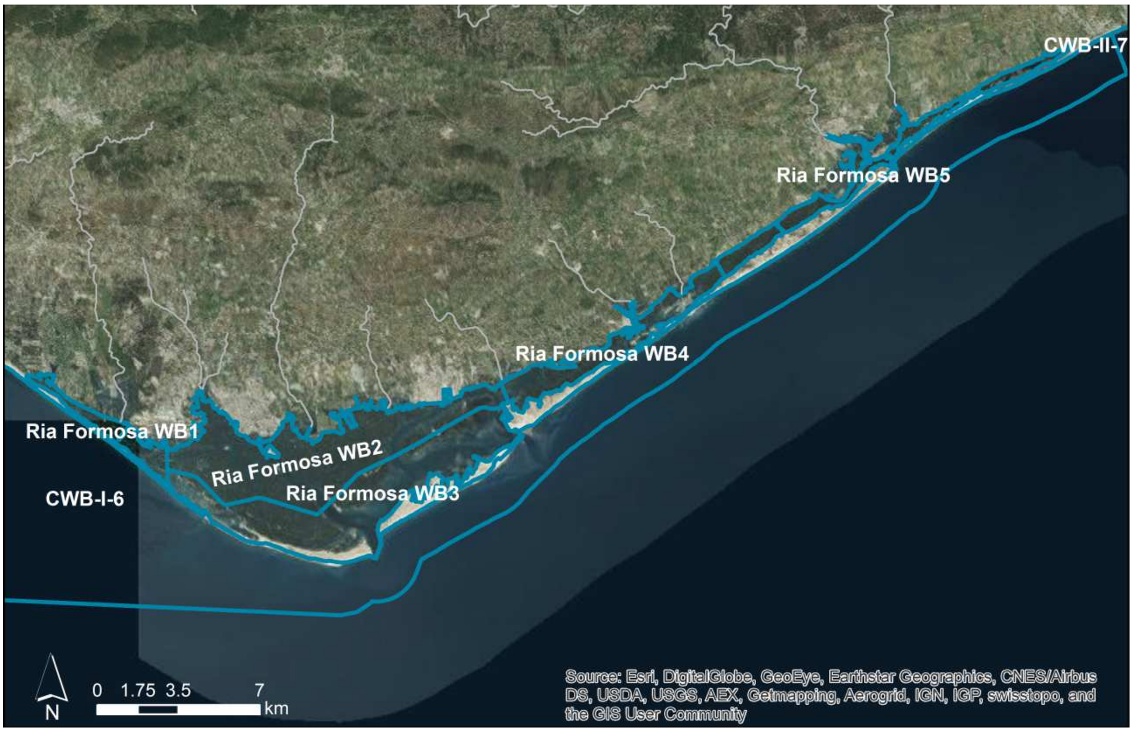


Figure 4.5. Water bodies in the Ria Formosa and adjacent coastal waters (blue), and surrounding river water bodies (grey). Data source: SNIAMB, http://sniamb.apambiente.pt/, December 2016.

Understanding the functioning of the Ria Formosa is crucial to preserve the intrinsic values of this ecosystem. Along time, in addition to biological studies, several others have been developed, tackling diverse aspects such as physical, chemical, geological processes and the lagoon dynamics coupling numerical modelling with field data (*e.g.*, Pilkey *et al.*, 1989; Falcão and Vale, 1990; Williams *et al.*, 1998; Vila-Concejo *et al.*, 2003; Newton *et al.*, 2003, 2010; Loureiro *et al.*, 2005, 2006; Goela *et al.*, 2009; Dias *et al.*, 2009; Pacheco *et al.*, 2010; Alcântara *et al.*, 2012, 2014; Fabião *et al.*, 2016; Malta *et al.*, 2016).

4.2 Hydrodynamics

The circulation in the Ria Formosa lagoon is primarily driven by tides, wind, atmospheric pressure and surface waves, while the riverine influence is almost negligible. Tides account for about 50% to 75% of water renewal in each tidal cycle (Newton and Mudge, 2003; Tett *et al.*, 2003; Mudge *et al.*, 2008). Its low mean depth, strong tidal currents and high rate of water exchanges, particularly close to the main channels and inlets, together with the low freshwater inputs, makes this lagoon vertically well mixed, seldom stratified (in terms of salinity and/or temperature), except during periods of heavy rainfall (Newton and Mudge, 2003). Fabião *et al.* (2016) also showed that circulation depends on the wind stress (intensity and direction) and bathymetry, which affects the residual circulation. Regarding the hydrodynamics of the Ria Formosa, it is important to bear in mind that, like other lagoons constrained by barrier islands, this system is in constant evolution due to overwash, salt marsh development, foredune erosion, aeolian processes, inlet dynamics and tidal currents (Ferreira *et al*., 2016).

Tides are semi-diurnal, like in the Tagus estuary, ranging from 0.5 m to 3.5 m in neap and equinoctial spring tides, respectively (mesotidal regime; Pacheco *et al*., 2010; Alcântara *et al*., 2012). Regarding the tidal propagation within the Ria Formosa, the knowledge is yet poorly investigated. However, Dias *et al*. (2009) and Jacob *et al*. (2012) reported that between the main tide constituents (MSF, K1, M2, M4, M6) occurs a predominance of the semi-diurnal and diurnal constituents. Furthermore, the component M4 is higher inside the lagoon than in the inlet zone, suggesting a tidal distortion in the interior area (Jacob *et al*., 2013).

Hydrodynamically, this lagoonal system can be divided into three different sectors. The east sector includes only the Lacém inlet, the central sector, includes the Fuzeta and Tavira inlets, and the western sector comprises the Ancão, Faro-Olhão and Armona inlets (Salles *et al*., 2005). The Ancão and Fuzeta are two artificially relocated inlets, Faro-Olhão and Tavira are artificially opened and stabilized inlets, while Armona and Lacém are considered natural inlets (Pacheco *et al*., 2011b).

The western sector of Ria Formosa plays a key role in the water renewal of the entire lagoon, representing approximately 90% of the total tidal prism (Salles *et al*., 2005; Pacheco *et al*., 2010). Faro-Olhão inlet is the main inlet (Pacheco *et al*., 2010; Cravo *et al*., 2013, 2014; Jacob *et al*., 2013; Jacob and Cravo, 2016), connecting the two main channels, Faro and Olhão channels and is responsible for about 60% to 70% of the Ria Formosa total tidal prism on neap and spring tides, respectively. The Armona inlet accounts for 25-37% of the total tidal prism, while the Ancão inlet contribution is very small (< 6%; Jacob *et al*., 2013).

The three inlets of the western sector have a high hydrodynamic interconnectivity. During the last eleven years, the Armona and Ancão tidal prisms decreased, due to changes in its morphodynamic and morphological features, while Faro-Olhão remained stable. Particularly, part of the Ancão inlet tidal prism was lost to Armona and Faro-Olhão inlets during spring tide, which can be associated to the eastward migration of Ancão inlet. In neap tide, the Armona inlet lost tidal prism to the Faro-Olhão inlet, due to its narrowing, while the Ancão remained stable (Jacob *et al*., 2013). Furthermore, considering data from 2011 (November and December) and 2012 (March and May), Faro-Olhão inlet showed flood prisms higher than ebb prisms in both tidal conditions, indicating a net circulation towards the coastal ocean through the Ancão and Armona inlets (Jacob and Cravo, 2016). However, this inlet also showed an ebb-dominated residual flow (October 2012 and March 2013; Rosa *et al*., 2016), suggesting an alternation in direction of the residual flow.

The study of current velocities during ebb and flood periods have demonstrated that in spring tide the Fuzeta and Lacém inlets are flood-dominated under a conventional interpretation (higher flood velocities and shorter flood duration) and are characterized by sediments import into the system (Salles, 2001; Pacheco *et al*., 2010, 2011a). Ancão, Faro-Olhão, Armona and Tavira inlets show an ebb-dominated behavior due to the higher mean and maximum ebb velocities and shorter ebb duration. This behavior also enhances the flush of sediments (Pacheco *et al*., 2010, 2011a; Rocha *et al*., 2016). However, it was not found a clear ebb or flood dominance in neap tide.

The natural inlets of this system tend to migrate in the west-east direction. This mechanism is directly associated with the most intense and prevailing winds, about 68% of the total occurrences from west, especially during winter (Ceia, 2009) and waves, 71% from southwest (Costa *et al*., 2001). However, winds from the Mediterranean (SE, known as "Levante") are also frequent, particularly during summer (about 25% of the total occurrences; Ceia, 2009). Offshore wave climate can be considered moderate to high, with annual mean wave heights of about 1 m and peak periods of 8.2 s (Costa *et al*., 2001; Pacheco *et al*., 2010), while within the Ria Formosa the waves are in the order of centimeters (Carrasco *et al*., 2009). Historically, changes in the morphology and in the position of the inlets have been reported. The opening and artificial stabilization (jetties) of the Faro-Olhão inlet occurred between 1929 and 1955 (Ferreira *et al*., 2016) with the purpose of ensuring the navigability to the harbors of Faro and Olhão (Pacheco *et* al., 2008) and resulted in a decrease of hydraulic efficiency in the Armona inlet (Ferreira *et al*., 2016). As a result, a change in tidal prism dominance from Armona to Faro-Olhão inlet occurred (Pacheco *et al*., 2010; Cravo *et al*., 2013; Jacob *et al*., 2013; Ferreira *et al*., 2016; Jacob and Cravo, 2016). The Tavira inlet was opened and stabilized between 1927 and 1985 (Vila-Concejo *et al*., 2006; Ferreira *et al*., 2016) in order to improve hydraulic efficiency. The Fuzeta inlet was artificially relocated in 1999 (Vila-Concejo *et al*., 2004) and more recently in 2011 (Ferreira *et al*., 2016). The Ancão inlet was artificially relocated in 1997 and in 2015 to improve water exchange between the western part of the lagoon and the adjacent ocean. A migration of 3500 m distance was recorded between the relocations of 1997 and just before the one of 2015 (Ferreira *et al*., 2016; Jacob and Cravo, 2016). The relocation of the Ancão inlet in 1997 demonstrated to improve the water renewal in relation to the previous 1979 configuration (Dias *et al*., 2009). The impact of the new relocation in November 2015 on the circulation and water characteristics remains to be studied. The Armona inlet was the dominant natural inlet in the system and has been in a stable location for several centuries, although its width is decreasing (Dias, 1988; Pilkey Jr. et al., 1989; Vila-Concejo *et al*., 2006), due to the achieved equilibrium between the Tavira and Faro-Olhão inlets (Alves, 2013). Due to the morphological interconnectivity between the inlets and the channels, morphological changes in any of them can modify, globally, the hydrodynamic regime in the Ria Formosa lagoon (Jacob and Cravo, 2016).

As already mentioned, the input of freshwater in this system is insignificant, except in Tavira, where the Gilão River discharges (Newton and Mudge, 2003; Barbosa, 2010). Gilão River has a low annual mean flow, < 2.5 $m^3 s^{-1}$ (Serpa *et al*., 2005; Barbosa, 2010). However, during periods of heavy rainfall the flow may increase significantly: daily maximums of about 265 $m^3 s^{-1}$ were recorded within the Gilão basin between 1975-1990 (SNIRH, http://snirh.pt/). The low freshwater input is directly linked to the low mean annual precipitation (614 mm in the period 1981-2010; IPMA, 2017). Besides the freshwater input from natural sources, there is also a daily input of effluent discharges from the WWTP into this system corresponding to about 2.5×10^4 m^3, which is low (two orders of magnitude lower) when compared with the daily exchange of water with the coastal ocean (Cravo *et al*., 2015). For this reason, salinity is normally high (approximately 36), and the Ria Formosa can be classified as a marine zone (Ferreira *et al*., 2003).

A daily rate of water renovation was calculated in the 1990's and it ranged from 80×10^6 m^3 in neap tide to 150×10^6 m^3 in spring tide (Neves *et al*., 1994). A recent estimate using the LIDAR bathymetry from 2011 indicates similar values: 50×10^6 m^3 in neap tide (1 m of tide height), 180×10^6 m^3 in spring tide (3.5 m of tide height) and 100×10^6 m^3 in intermediate tide (2 m of tide height) (J. Luis, personal communication, University of Algarve). The difference of volumes between spring and neap tides leads to differences in the currents velocities and, consequently, affects the residence time inside the lagoon. During spring tide the tidal currents are stronger, decreasing the residence time, while in neap tide the residence time increases (Dias *et al*., 2009; Dias and Sousa, 2009).

The residence times at or close to the inlets are smaller than one day (Martins *et al*., 2003; Tett *et al*., 2003; Duarte *et al*., 2008), in the inner channels are about 4-5 days (Duarte *et al*., 2008) and in the inner zones of the lagoon can be up to 14 days (Mudge *et al*., 2008). Fabião *et al*. (2016) also estimated the mean residence times of the effluents discharged from the four WWTP located in the western sector of the lagoon, obtaining values from 7 days to 18 days.

Tidal current velocities at the main inlets are higher (around 2 m/s) when compared to the channels (≤ 0.8 m/s; Lima and Vale, 1980; Cravo *et al*., 2014; Fabião *et al*., 2016; COALA project, not published), putting in evidence that the tidal velocity tends to decrease towards the inner zones of the lagoon (Dias and Sousa, 2009; Brito, *et al*., 2010). Valença *et al*. (2011) in the study reporting 25 years of data collection in the Ria Formosa lagoon also described that the current velocities at artificial inlets overpassed 2 m/s, while 1 m/s was found at the natural inlets. These differences of velocities from the inlets to the inner regions of the Ria Formosa influence the sedimentary regime along the lagoon. The sediment characteristics differs mainly from coarse sand along the channels/inlets to muddy-sand and mud towards to the hinterland areas (Falcão and Vale, 1990; Figure 4.6), where the tidal hydrodynamics is less pronounced (Mudge *et al*., 2008).

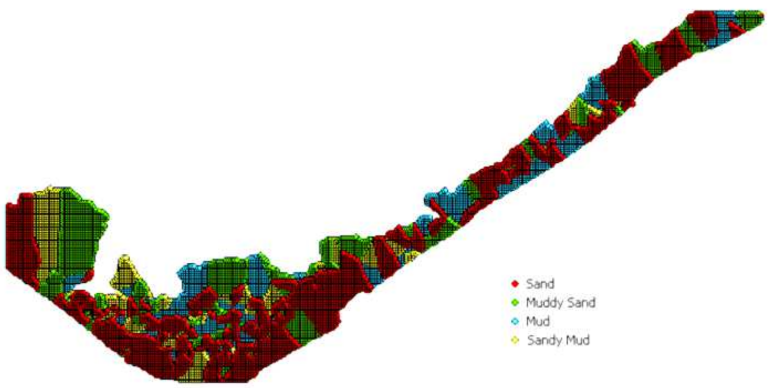


Figure 4.6. Distribution of sediment types in the Ria Formosa lagoonal system. Adapted from: Rodrigues *et al*. (2005).

4.3 Biogeochemical dynamics and water quality

Many studies have been carried out in the Ria Formosa, mainly after the 1960's-1970's, to analyze the water characteristics or evaluate its quality (e.g., Silva and Assis, 1970; Lima and Vale, 1977; Cunha and Massapina, 1984; Falcão *et al*., 1985; Brockel, 1990; Cortez, 1992; Thiele-Gliesche, 1992). However, these data are scattered, with larger temporal and spatial discontinuities, preventing an accurate evaluation of the historical evolution of water quality. Ria Formosa is not spatially homogeneous and is distinctly affected by sources of pressure, with different magnitudes. Some of those studies, from the late 80's, were conducted within the scope of PhD thesis, showing a broader spatial coverage along the Ria Formosa (Newton, 1995), or annually intense sampling frequency, mainly at the main inlets and channels (Falcão, 1996). Since the 1990's, and particularly after 2000's, within the scope of the implementation of the WFD, much more studies have been performed (Cravo, not published, 1992; Newton *et al*., 2003, 2010, 2014; Ferreira *et al*., 2005, 2006; Loureiro *et al*., 2005; Pereira *et al*., 2007; Goela *et al*., 2009; Barbosa, 2006; Barbosa, 2010; Brito *et al*., 2009, 2010, 2012b). Nevertheless, most of these works focused on the western sector and are not constant along time. Continuous monitoring programs are almost inexistent, with exception of the VQM project, that covered several stations within the Ria Formosa lagoon, from 1985 until 2009 (Valença *et al*., 2011). Unfortunately, these data are not available to endorse a temporal evolution analysis. In 2010, within the context of the WFD, and in order to classify the ecological status of the water bodies, EEMA project was implemented at a national level, contemplating also the Ria Formosa (APA, 2012e). The acquired data in this context is available at the APA site (https://www.apambiente.pt).

Taking into account the results of these studies and some recent results obtained at the three inlets of the western sector of the Ria Formosa, in the period 2011-2013 (COALA project), a spatial and temporal analysis of the physical, chemical and biological variables was performed, similarly to the characterization performed to the Tagus estuary.

Water temperature, salinity, pH and dissolved oxygen

Water temperature at several stations along Ria Formosa, encompassing the five water bodies, ranged from 10 to 30 ºC (1967-2013 data). Seasonally, temperature was, as expected, higher during the summer (June until September), particularly in shallow areas with weak hydrodynamic conditions (inner zones of the lagoon, as represented by Ria Formosa-WB2; Figure 4.7). Minimum values were also observed in the shallow-inner areas of the lagoon during winter conditions. Regarding salinity (Figure 4.7), for most of the sampled sites, observed values are characteristic of ocean waters (close to 35), except during periods of intense rainfall or in stations close to the Gilão river (Ria Formosa-WB5). Between 1985 and 2009 salinity ranged from 5.7 to 38.8 (Valença *et al*., 2011). Recent values (2011-2013) from the main inlets (western sector) were within this range, although comprising a narrow range of values from 34.4 to 37.3 (COALA Project, unpublished data). Seasonally, the highest values were found in summer, while the minimum values were observed during winter or under heavy rainfall periods (Figure 4.7), as expected.

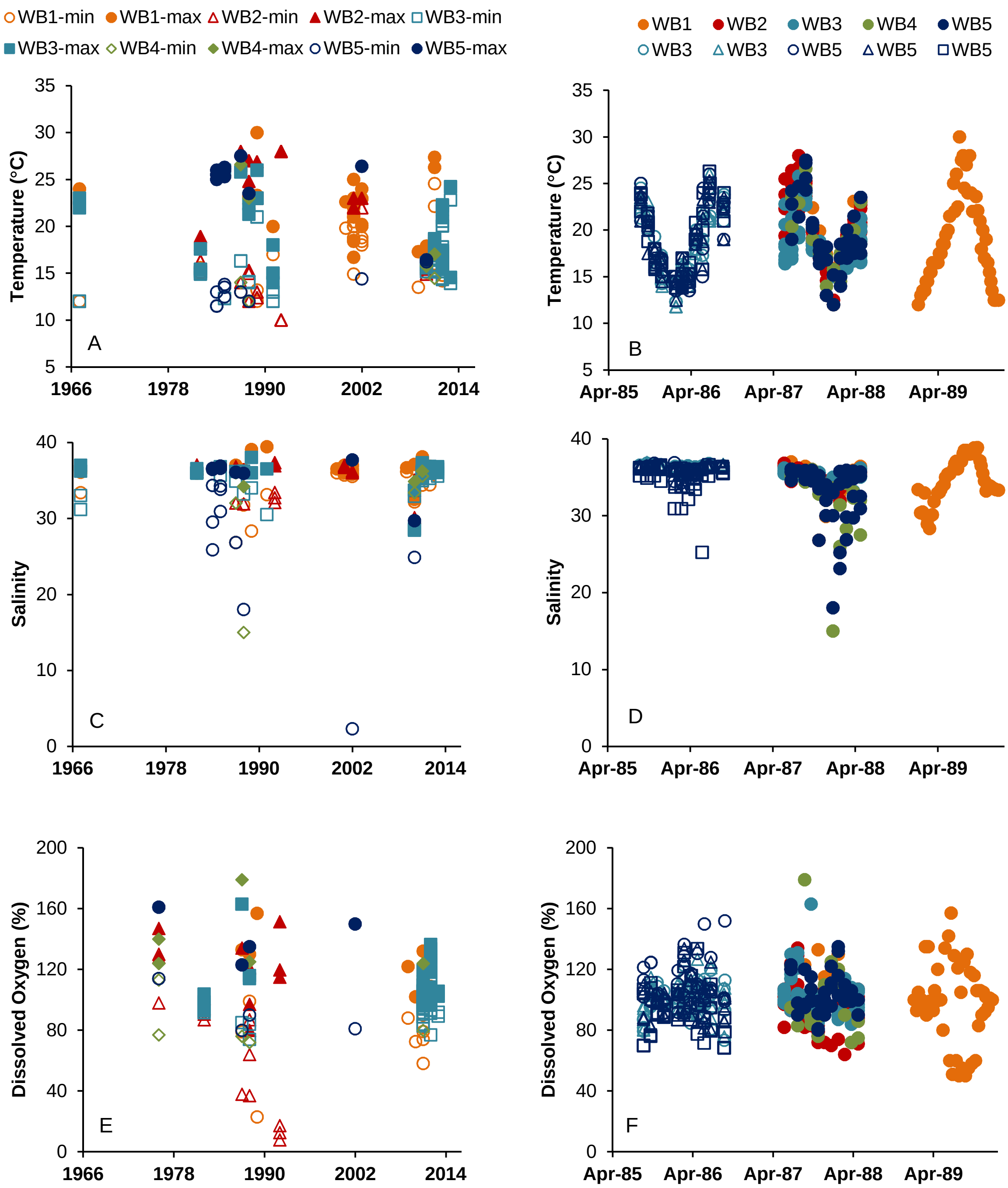


Figure 4.7. Water temperature, salinity and oxygen annual variation from 1967 to 2013 (A, C, E; minimum and maximum values; all data acquired) and seasonal variation (B, D, F) in each water body of Ria Formosa. In the graphics at the right the filled symbols correspond only to Newton (1995) data and the empty symbols to Falcão (1996) data.

Regarding pH, observations between 1985 and 2009 ranged from 7 to 8.5 (Valença *et al*., 2011). More recently, the lowest values observed at the main inlets were higher, within the range of 7.75-8.5 (2011-2013; COALA Project, unpublished data).

During summer the solubility of oxygen can be reduced, since this parameter is strongly influenced by temperature and salinity and at this time of the year Ria Formosa becomes hypersaline (Tett *et al*., 2003). Spatially, in areas where the residence time is high and the exchange of water is limited, a depletion of oxygen was observed, as found in the 1990's near the Faro Dock (8% in 1992 in Ria Formosa-WB2; Figure 4.7). This effect was intensified especially in periods of larger accumulation of organic matter (Mudge *et al*., 2007; A. Cravo, personal communication). Since the waters of Ria Formosa are considered shellfish waters by the Decree-law 236/98, percent oxygen saturation must be > 80% to comply with this normative (Valença *et al*., 2011). Most of the available data conform to this value, except some values observed in the Ria Formosa-WB2, in the urban center of Faro, between 1987-1992 (Figure 4.7), which was associated with the high anthropogenic influence in the area (Valença *et al*., 2011). After 2000, apparently, minimum oxygen saturation values increased (> 60%; Valença *et al*., 2011). Near the inlets (Ria Formosa-WB3 and Ria Formosa-WB1), the oxygen saturation frequently reaches values of supersaturation (> 100%), due to the strong mixing with the oxygenated marine waters (Figure 4.7). Seasonally, maximum dissolved oxygen saturation is observed during spring and autumn, typically associated with the increase of photosynthesis rate (Figure 4.7), while by the end of summer the minimum values tends to occur (Valença *et al*., 2011).

<u>Nutrients</u>

Several studies revealed a decreasing trend of nutrients concentration from the 1970's to present (Figure 4.8, Table 4.1). Recent data from EEMA project (2010) also suggest that nutrients concentrations decreased, at least by one order of magnitude, when compared with those observed in the late 1980's (Newton, 1995). This trend was already pointed out by the end of the 1990's (DGA, 2000) and, more recently, based on a 25 years data analysis (1985-2009; Valença *et al*., 2011). Several authors have also suggested this nutrients' reduction, particularly in the western sector of Ria Formosa (Loureiro *et al*., 2006; Pereira *et al*., 2007; Barbosa, 2010; Brito, *et al*., 2010; Cravo *et al*., 2015).

Several factors may have contributed to the observed decrease and the improvement of the water quality in the Ria Formosa, such as: the better circulation promoted by several interventions in terms of the relocation/opening of the Ancão inlet in 1997 (Vila-Concejo *et al*., 2004), the dredging of the main channels in 1999 and 2000 (Newton and Icely, 2002; Loureiro *et al*., 2006; Ribeiro *et al*., 2008), the improvement and upgrade of the treatment of the domestic and industrial effluents (Barbosa, 2010; Ferreira *et al*., 2012), and the decrease of fertilizers to comply with the Nitrate Directive (Stigter *et al*., 2006).

Table 4.1. Observed ranges concentrations of nutrients and chlorophyll *a* (Chla) in the Ria Formosa lagoon.

Period	NH_4^+ (μM)	NO_3^- (μM)	NO_2^- (μM)	PO_4^{3-} (μM)	SiO_4^{4} (μM)	Chla (μg/L)	Reference
1967-1976	-	-	0.14-0.71	0.64-5.16	-	0.7-12.17	Silva and Assis (1970) [a] Lima and Vale (1977) [a, b]
1982-1989	n.d.-54.87	n.d.-326.33	0.01-4.80	n.d.-6.93	n.d.-790.73	0.10-8.30	Cunha and Massapina (1982) [a, b] Falcão *et al*. (1985) [a, b] Barbosa (1989) [a, b] Brockel (1990) [a, b] Cortez (1992) [a] Thiele-Gliesche (1992) [a, b] Newton (1995) [a, b] Falcão (1996) [a]
1990-1999	n.d.-66.70	n.d.-60	n.d.-6.60	0.20-21.37	n.d.-236.71	0.18-19.22	Cortez (1992) [a, b] Cravo, not published (1992) [b] Condinho (2000) [a, b] Barbosa, 2006 [a, b]
2000-2002	n.d.-4.60	n.d.-15-40	0.03-0.58	0.03-1.30	n.d.-9.89	n.d.-5.10	Loureiro *et al*. (2005) [a, b] Pereira *et al*. (2007) [a, b] Goela *et al*. (2009) [a, b]
2001-2002	n.d.-247.3	n.d.-39.6	-	n.d.-97.6	n.d.-293.6	n.d.-358.7	Cravo *et al*. (2015) [c]
2006-2008	0-6	0-9	0-0.4	0-1.50	1-20		Brito (2010) [a, b]
2009-2010	0.50-8.36	0.26-12.15	0.23-0.58	0.09-0.79	0.35-20.52	n.d.-6.2	EEMA project (2010) [a, b] Alcântara *et al*. (2012) [a] Ovelheiro (2011) [a]
2011-2013[c]	0.01-3.49	n.d.-6.89	n.d.-0.70	n.d.-0.55	0.28-5.72	n.d.-2.52	Cravo *et al*. (2012) [a] Cravo *et al*. (2013) [a] Cravo *et a*l. (2014) [a] COALA project, unpublished data [a]

[a] Data from stations located at the inlets and/or in their vicinity.
[b] Data from stations located at the inner areas of the lagoon.
[c] Data from stations located in the vicinity of WWTP.
n.d.: not detectable.

Spatially, the highest ammonium and phosphate concentrations were found in the inner areas of the lagoon, namely near Faro and Tavira (Figure 4.8). In those zones, water renewal is weaker, while agriculture practices (using fertilizers) and sewage discharges are more intense (Newton and Mudge, 2005). Runoff from agricultural fields is recognized as the main source of nutrients in both the western and eastern sectors of the lagoon (Newton *et al*., 2003; Barbosa, 2010). Additionally, effluents can also be an important source of these nutrients in the Ria Formosa, particularly in the vicinity of the WWTP as recorded near the cities of Faro and Olhão (e.g., Newton, 1995; Valença *et al*., 2011, Cravo *et al*., 2015). At places very close to the discharge points, nutrient concentrations can be orders of magnitude higher than in the main channels or near the inlets (Cravo *et al*., 2015; Table 4.1). Silicate and nitrate concentrations were highest near Tavira or at stations in the Ria Formosa-WB4 (Figure 4.8), due to the influence of the freshwater input from the Gilão River and Mosqueiros Stream, respectively, whose waters were also enriched in fertilizers. The lowest nutrients' concentrations were found at the stations near the main inlets (Figure 4.8) as confirmed by several authors (Falcão,1996;

Newton and Mudge, 2005; Barbosa, 2010; Valença *et al*., 2011; Cravo *et al*., 2015). However, during upwelling events a different pattern may be depicted. Nutrients, in particular nitrate, may increase at the main inlets, due to their import from the adjacent ocean (Barbosa, 2010; Alcântara *et al*., 2012; Cravo *et al*., 2014; Rosa *et al.*, 2016).

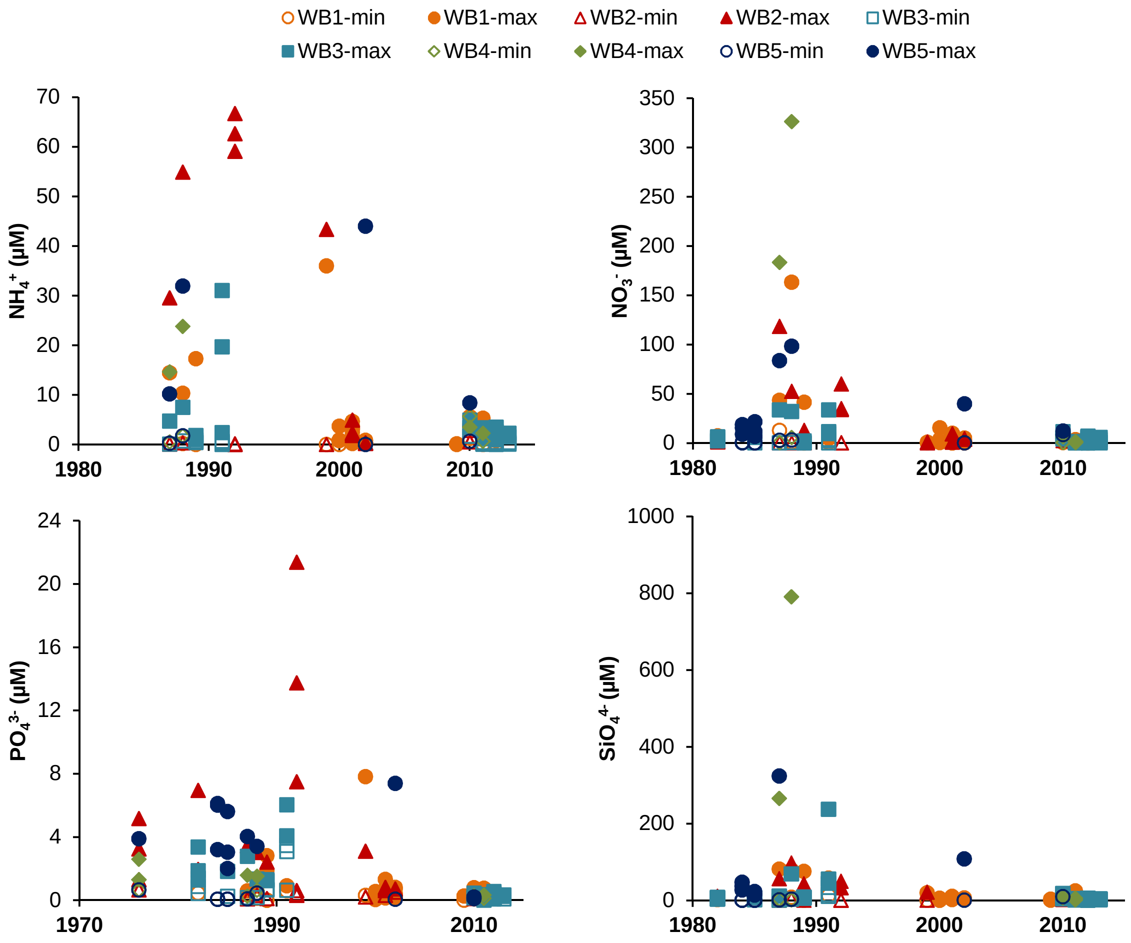


Figure 4.8. Ammonium (NH_4^+), nitrate (NO_3^-), phosphate (PO_4^{3-}) and silicate (SiO_4^{4-}) annual minimum and maximum concentrations between 1976 and 2013 (all data) in each water body of Ria Formosa.

Seasonally, nutrients decrease during spring and summer, as showed in Figure 4.9 for nitrate and silicate during the spring of 1988, resulting from the increase of their consumption by phytoplankton (Barbosa, 2010). Phosphate may, however, exhibit a different seasonal behavior, with maximum values during summer (Barbosa, 2010; Figure 4.10). This can be associated with the intensification of organic matter decomposition and remineralization in sediments, benthic bioturbation and phosphorus release from sediments during periods of water temperature increase (Falcão and Vale, 1998). Furthermore, the intensification of inputs of wastewater discharges during this season may contribute to increase the phosphate availability (Newton and Mudge, 2005). Ammonium (Figure 4.10) can depict a similar seasonal pattern, but in summer can still attain minimum concentrations due to an increase of the nitrification rate (Gurel *et al*., 2005). The winter maximum of the nutrients is usually promoted by the increase of freshwater inflow and land runoff (Newton *et al.*, 2003; Newton and Mudge, 2005), particularly during the season when the phytoplankton growth is limited.

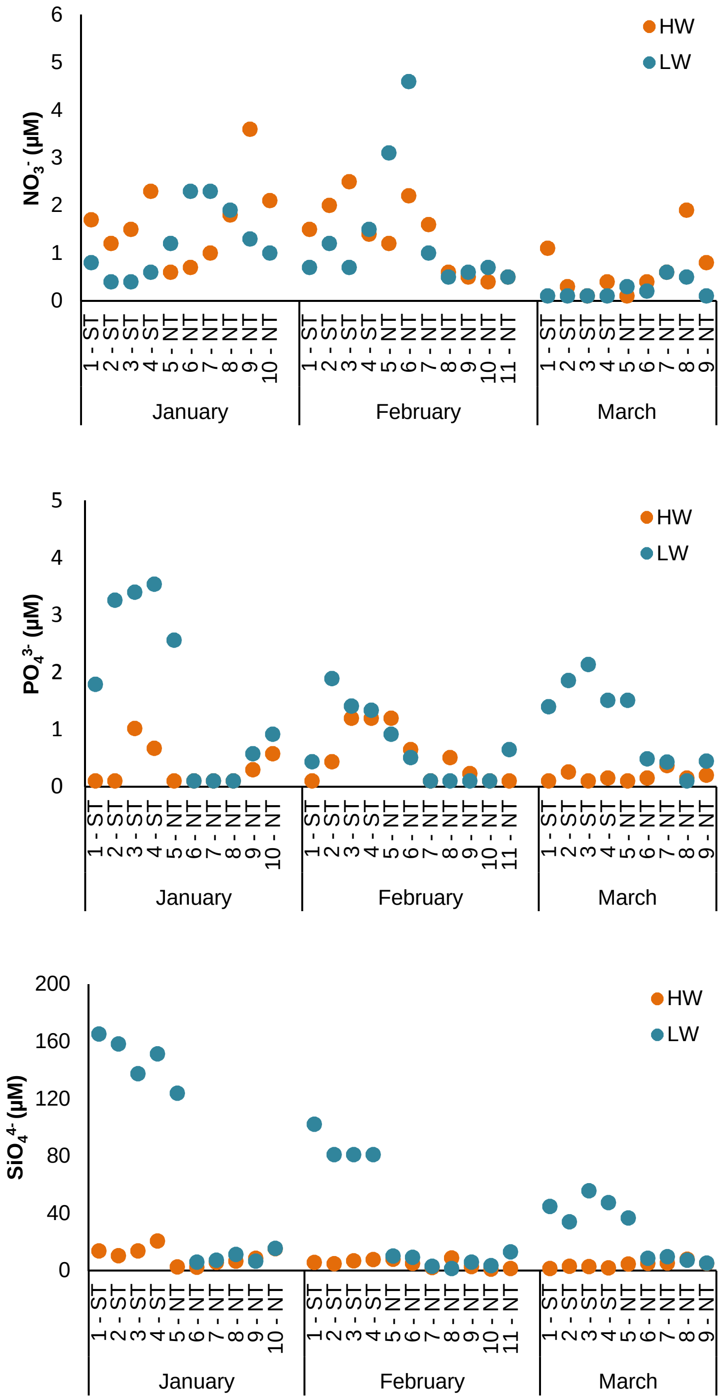


Figure 4.9. Nitrate (NO_3^-), phosphate (PO_4^{3-}) and silicate (SiO_4^{4-}) daily concentrations of spring tide (ST) and neap tide (NT) measured on January 1988 (10 days), February 1988 (11 days) and March 1988 (9 days) (Falcão, 1996).

Regarding the tidal effect, the differences in the nutrients' concentrations (nitrate, phosphate and silicate) between high and low water are magnified in spring tide (Figure 4.9, relative to January to March of 1998; Falcão, 1996), due to the higher dilution effect promoted by the larger volume of water exchanged. In neap tide, the currents are weaker and the residence times are longer, which may intensify the biological activity in the waters comparatively to that in spring tide. It is also known that along a complete semi-diurnal tidal cycle the water characteristics change. The nutrients pattern of variation tends to behave in antiphase with the sea level height (Alcântara *et al*., 2012; Cravo *et al*., 2013, 2014), confirming that, in general, a tidal dilution effect occurs during high water, since ocean waters are poorer in nutrients than Ria Formosa waters. This increase of nutrients at low tide may be associated with the greater availability of nutrients within the Ria Formosa provided either by runoff or by higher diffusion from the sediments (Falcão and Vale, 1990), from tidal advection particularly in a period when the water column is shallower. Data from consecutive tidal cycles acquired at the bridge of Faro beach in 1989 (Ria Formosa-WB1; Figure 4.11; Newton, 1995) show that observed nutrient concentrations were considerably higher than the highest concentrations observed at the closest inlet, the Ancão inlet in 2011 (<2 µM NH_4^+, <3 µM NO_3^-, <0.3 µM PO_4^{3-} and <6 µM SiO_4^{4-}; Cravo *et al*., 2013, 2014).

The sources and processes that affect the availability of nutrients in coastal lagoons may distort the Redfield ratio. In the Ria Formosa, the limiting nutrient is usually nitrogen (DIN/P ratio < 16 and DIN/Si ratio < 1), as reported by Newton and Mudge (2005), Loureiro *et al*. (2005, 2006), Alcântara *et al*. (2012), Cravo *et al*. (2013, 2014), in contrast to the Tagus estuary. This fact has been consistent over time, since the 1980's until 2011 (e.g. Figure 4.12 and Figure 4.13). Valença *et al*. (2011), in the evaluation of the temporal evolution of the water quality within the Ria Formosa for the period 1985-2009, also observed this behavior. In coastal systems, the limiting nutrient for primary production may vary seasonally (Falcão and Vale, 1998), but in the Ria Formosa the limitation of nitrogen is intensified during summer due to the high nitrogen consumption relative to phosphorus.

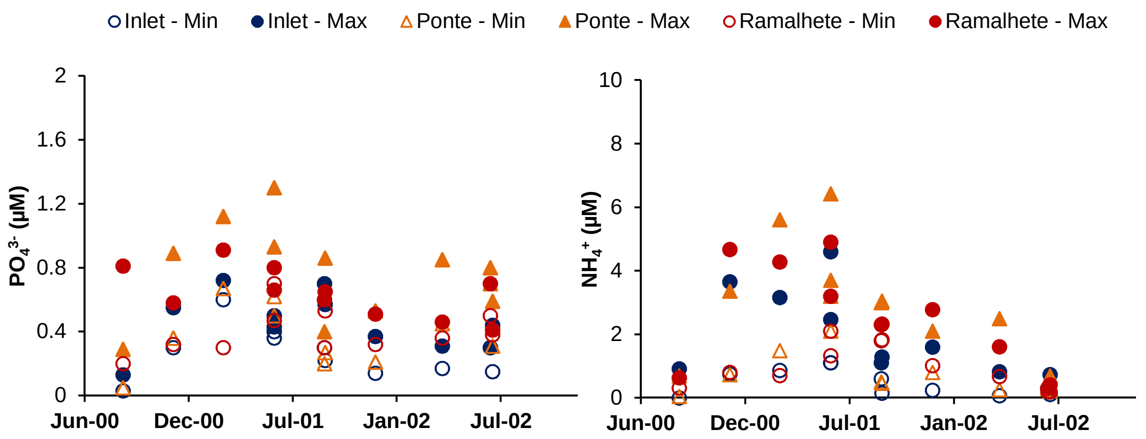


Figure 4.10. Seasonal variation of phosphate (PO_4^{3-}) and ammonium (NH_4^+) minimum and maximum concentrations in the Ancão inlet (western zone of the lagoon), Ponte (bridge of Faro beach) and Ramalhete (located in the inner zone of the Ria Formosa).

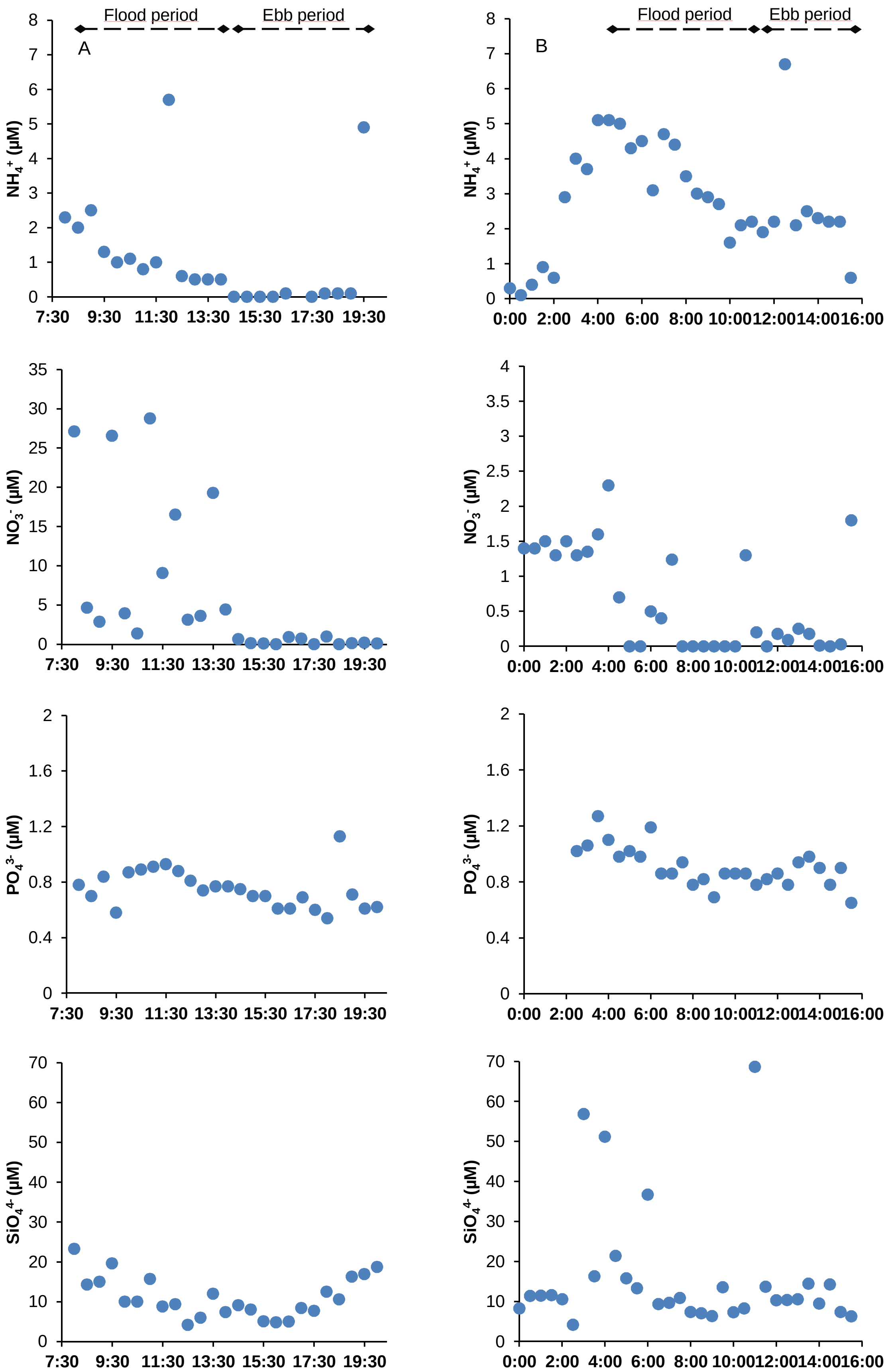


Figure 4.11. Nutrients concentrations (ammonium, nitrate, phosphate and silicate) at Ponte (bridge of Faro beach) during two complete semidiurnal tidal cycles, both on September 1989. Column A corresponds to spring tide and B to neap tide (Newton, 1995).

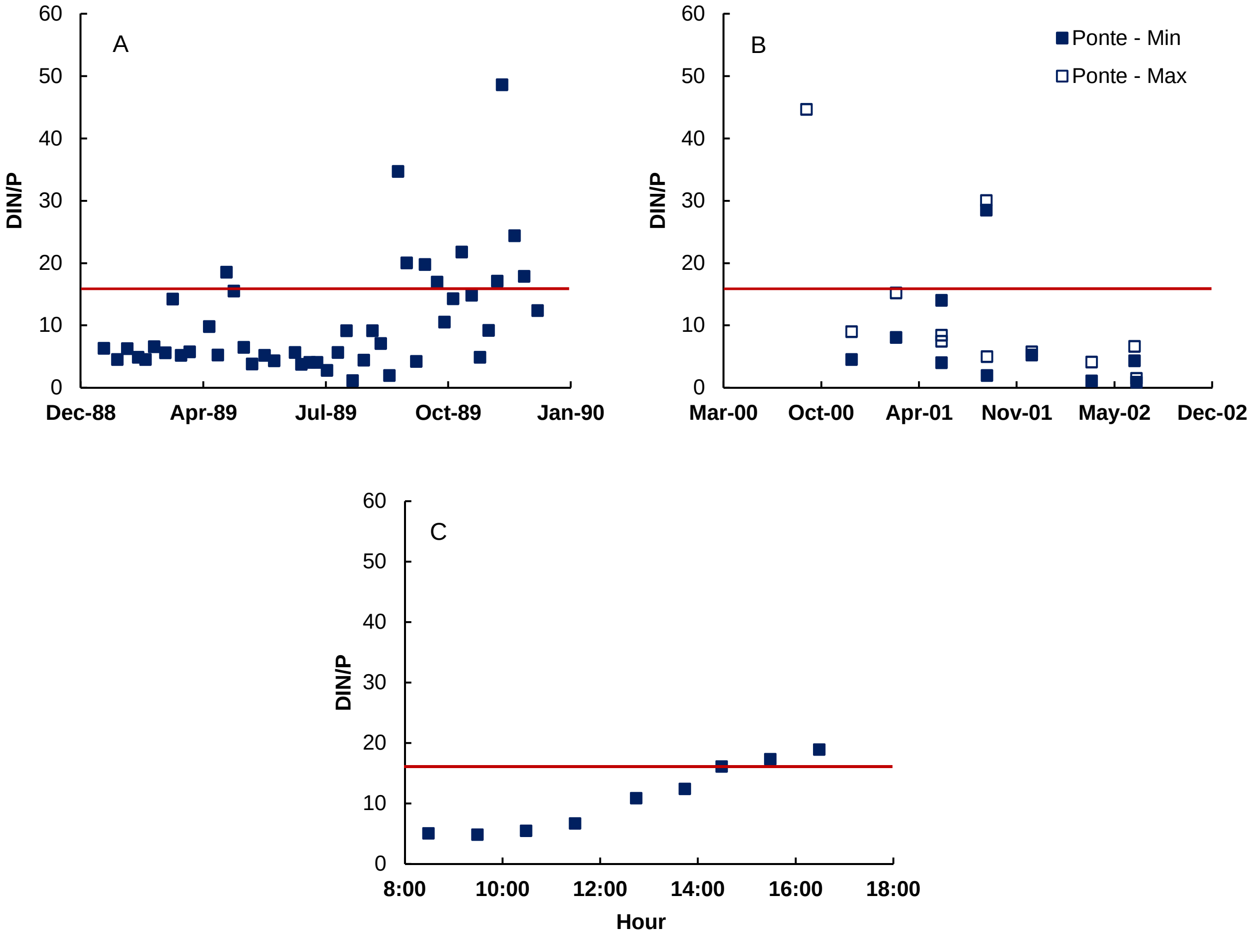


Figure 4.12. Mean DIN/P ratio at Ponte (bridge of Faro beach) during the year of 1989 (A, Newton, 1995), DIN/P ratio range from 2000 to 2002 (B, Loureiro *et al*., 2005; Pereira *et al*., 2007) and mean DIN/P ratio at Ancão inlet during a complete semidiurnal tidal cycle in November 2011 (C, Cravo *et al*., 2013, 2014).

Chlorophyll *a*

Chlorophyll *a* ranged from 0.1 to 12.2 µg/L between 1967 and 2013 in the Ria Formosa (Figure 4.14). No evident temporal pattern was observed and this proxy of phytoplankton biomass had a homogeneous behavior between 1990 and 2009, despite the maximum values found in 2002 and 2003 (about 30 µg/L; Valença *et al.*, 2011). Spatially, the largest concentrations were generally found in the inner zones of the lagoon and the lowest concentrations near the main channels and/or inlets (Barbosa, 2010; Cravo *et al*., 2015). Seasonal cycles with a maximum primary biological productivity in summer (unimodal cycle) were observed (Assis *et al.*, 1984; Falcão *et al.*, 1991), particularly in the inner zones, correlated with temperature and availability of light (Barbosa, 2010). However, bimodal annual cycles have also been observed, typically at the inlets (Barbosa, 2010), with bloom peaks in spring and autumn. The concentrations of chlorophyll *a* were mostly below 6 µg/L (Figure 4.14), indicating a High-Good Status of the water quality in Ria Formosa (EC, 2008), as reported by Goela *et al*. (2009) at the western end of the lagoon.

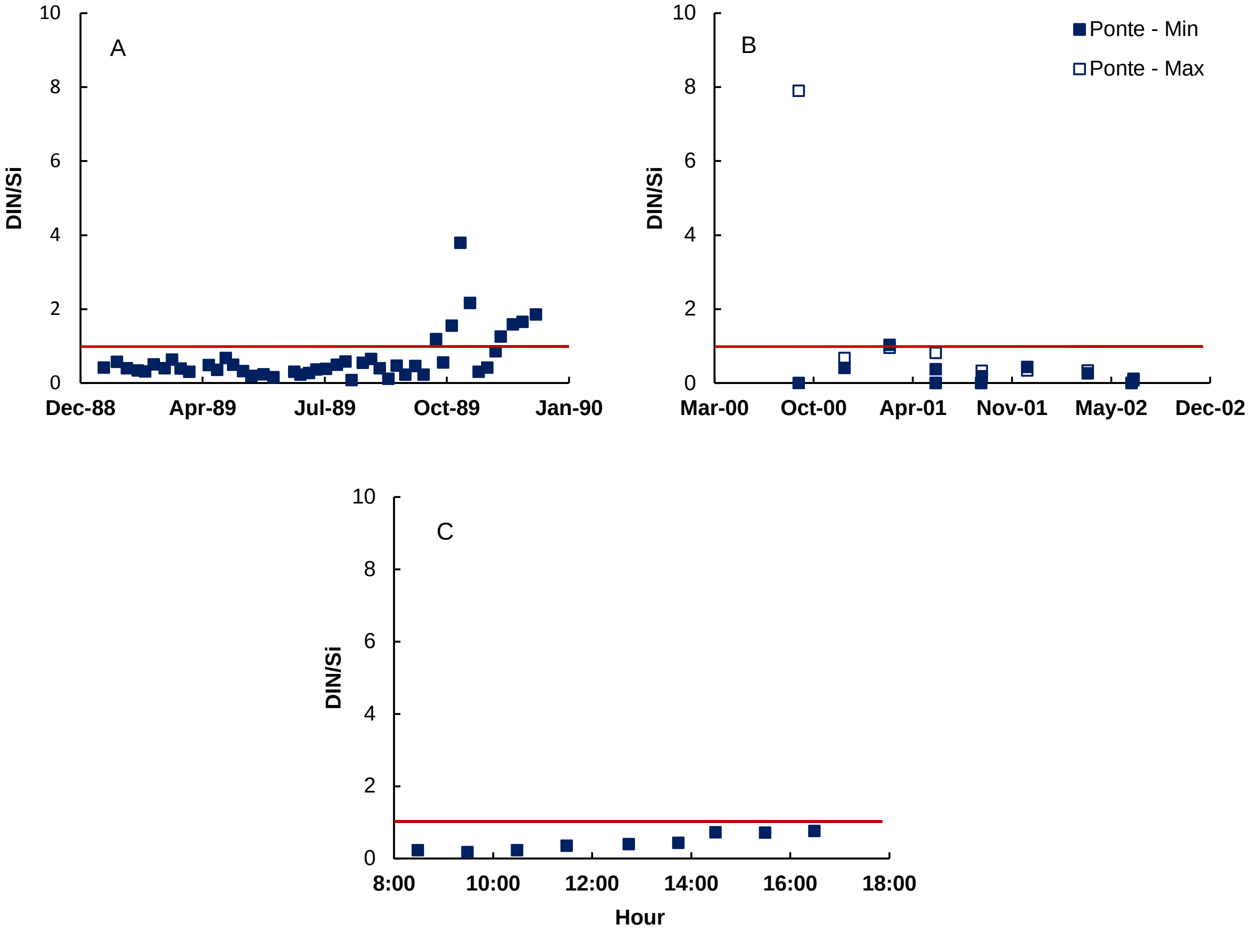


Figure 4.13. Mean DIN/Si ratio at Ponte (bridge of Faro beach) during the year of 1989 (A, Newton, 1995), DIN/Si ratio range from 2000 to 2002 (B, Loureiro *et al*., 2005; Pereira *et al*., 2007) and mean DIN/Si ratio at Ancão inlet during a complete semidiurnal tidal cycle on November 2011 (C, Cravo *et al*., 2013, 2014).

Eutrophic conditions have been reported (along with depletion of dissolved oxygen events), although these just occurred locally, particularly close to the discharges of the WWTP (Mudge *et al*., 2008; Cravo *et al*., 2015). However, according to Ferreira *et al*. (2003), which evaluates the potential of vulnerable zones to eutrophication based on the three indices (see section 3.3), the Ria Formosa was classified in “Moderate Low” (OEC), “Moderate” (OHI) risk, not being considered a vulnerable zone to eutrophication. Using the proposed methodology of Brito *et al*. (2012b) to assess the ecological quality status of the water bodies of Ria Formosa, all of those were classified as in High Ecological Status, since chlorophyll *a* levels are relatively low (< 5.3 µg/L, the reference value for coastal water lagoons) and the water exchange with the adjacent ocean is high. The relatively low concentrations of chlorophyll *a* observed in the Ria Formosa can be also associated with the shellfish communities, since these organisms can remove a part of the primary producers from the water column by filtration/consumption (Brito *et al*., 2012b).

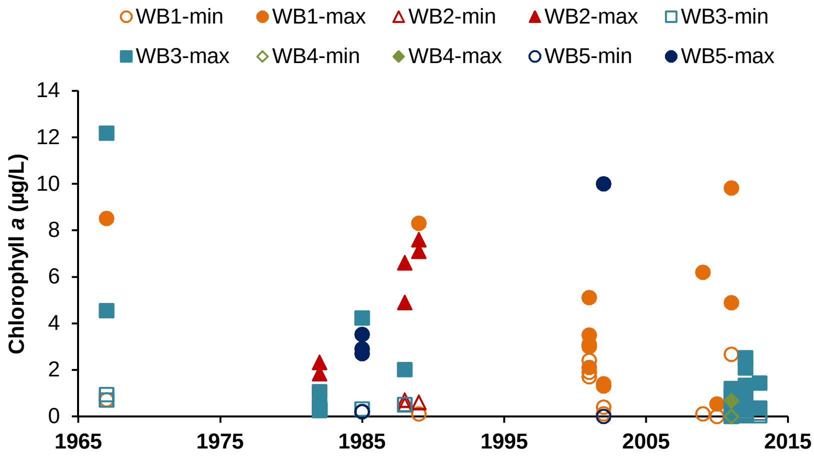


Figure 4.14. Chlorophyll *a* minimum and maximum concentrations from 1967 to 2013 (all data acquired) along the water bodies of the Ria Formosa.

Regarding the phytoplankton community variability on a long-term scale, this approach is still poorly established (Loureiro *et al*., 2006; Barbosa, 2010). However, it is known that the biomass of phytoplankton in this lagoon is, in general, dominated by the group of cryptophytes (nanoplanktonic flagellates; Barbosa, 2006; Pereira *et al*., 2007), while in summer the diatoms can also predominate (Barbosa, 2006).

4.4 Pressures

Considering the pressures groups systematized by APA (see section 3.4) it is possible to identify similar pressures between the Tagus estuary and the Ria Formosa lagoon, although of lower magnitude on this last system.

In Ria Formosa lagoon, the main non-point sources are agriculture (e.g., fertilizers and land runoff), livestock (e.g., production of organic matter), golf (e.g., input of nutrients by runoff) and diffuse domestic untreated wastewaters. Considering the point sources, sewage discharges are the most important ones (Ferreira *et al*., 2003; MAOTDR, 2004; MAMAOT, 2012). Most of the WWTP started to operate in the early 1990's (Cravo *et al*., 2015) at the main cities around the Ria Formosa. Since the 2000s, like for the municipalities bordering the Tagus estuary, important investments were made to implement, improve and upgrade the treatment of urban effluents, including secondary and/or tertiary treatment (from Águas do Algarve, http://www.aguasdoalgarve.pt/). Regardless that effort, sewage discharges still represent an important pressure on water quality of Ria Formosa (Cravo *et al*., 2015). This ecosystem, like many others European coastal lagoons, represents a very attractive and popular environment where urban and tourism development is evident. Thus, the population may increase about 4-5 times during the summer season (Newton *et al*., 2014), which contributes to the regional economy, but also to the increase the pressure into the lagoon (Cravo *et al*., 2015). Sometimes the capacity of the WWTP may be overpassed due to the seasonal population increase (Newton *et al*., 2014).

Few studies approaching the quantification of the dominant pressures, both point and diffuse, have been developed, and the methods of estimation are not the same. Carneiro *et al*. (1998) estimated the nutrients loads to the Ria Formosa basin from agricultural, domestic and industrial outputs in the period 1984-1994. Taking into account the estimation for the year of 1994, the total loads into the Ria Formosa were 614 ton N and 47 ton P. Comparatively to 1984, a decrease in nitrogen and phosphorus was observed in the low season, due to the implementation of WWTP in the early 90's. Nevertheless, an increase was observed in summer due to the increase of population. Ferreira *et al*. (2003), focused on the three main sources of nutrients for this lagoon (WWTP, domestic effluents without wastewater treatment and non-point sources), pointed out that the contribution of non-point sources was dominant (58%) relatively to the treated and untreated sources (42%). Total nitrogen loads (421 ton N per year) were significantly higher than phosphorus loads (83 ton P per year), assuming that the average nitrogen and phosphorus removal efficiencies at the WWTP are 36% and 53%, respectively. More recently, within the scope of the FORWARD project (Framework for Ria Formosa Water quality, Aquaculture and Resource Development), Ferreira *et al*. (2012) estimated, based on 2007 and 2008 data, that the main nutrient sources in the Ria Formosa are WWTP (45% N – 450 ton per year, 32% P – 67 ton per year) and agriculture (diffuse source; 55% N, 68% P), that include surface waters (14% N – 146 ton per year and 21% P – 44 ton per year) and discharge of contaminated submarine groundwater/aquifers through the sediments (41% N – 414 ton per year, 47% P – 98 ton per year).

Looking into more detail to the pressures in each of the water bodies of the Ria Formosa, based on the data provided by APA relative to 2006, 2009 and 2012, the predominant pressures are identified as point sources, unlike those in the previously reported studies. The dominant diffuse sources in the system are livestock and agricultural/forestry activities. The highest loads were observed in Ria Formosa-WB2 (2 ton N per year and 0.1 ton P per year) and Ria Formosa-WB5 (16 ton N per year and 2 ton P per year). This spatial pattern is linked with the higher population density in the western area of the lagoon and to the area with greater agricultural activity in the eastern side (Newton *et al*., 2003). Nevertheless, the evaluation of nutrients loads into this lagoon through diffuse sources requires further investigation (Ferreira *et al*., 2012), since these contamination processes, including submarine groundwater discharges, are poorly understood. Regarding point sources, nutrients loads in Ria Formosa-WB2 were significantly higher (272 ton N per year and 47 ton P per year) than in the remaining water bodies (between 0.04-133 ton N per year and 0.02-6 ton P per year), which may be related with the main urban areas surrounding this water body (Faro and Olhão).

The artificial opening of the Ancão inlet in 1997 (Vila-Concejo *et al*., 2004) and the dredging of the main channels in 1999 and 2000 (Newton and Icely, 2002; Loureiro *et al*., 2006; Ribeiro *et al*., 2008) – involving about 2650000 m^3 of sediments (Ramos and Dias, 2000) – were processes directly associated with the hydromorphologic pressures (APA, 2012d). Other hydromorphologic pressures in the Ria Formosa were the construction of bridges (bridge of Faro beach and Tavira), jetties in the inlets and piers (Faro-Olhão inlet and Fuzeta village, respectively). Nevertheless, these pressures are not considered to be significant, having low hydrodynamic impact. In contrast, presently, all the structures built in the cities of Faro and Olhão, together with the harbour of Faro – located in the Ria Formosa-WB2 – are identified as the most significant hydromorphological pressures in this system (APA, 2012d).

The biological pressures affecting the ecology of Ria Formosa lagoon are mainly fishing (recreational and commercial) and aquaculture activities within the lagoon (Ria Formosa-WB2 and Ria Formosa-WB4) and located off the coast of the Armona island (APA, 2012d).

5. Final considerations

The Tagus estuary and the Ria Formosa were selected as case studies within the project UBEST, which aims at improving the understanding of the biogeochemical buffering capacity of systems located in the sea-land interface and of their vulnerability to climate change and anthropogenic pressures.

The ecological values of both systems are well recognized, as they both harbor important protected ecosystems. The Tagus estuary is one of the largest estuaries in Europe with an area of about 320 km^2. The Ria Formosa is considered the most important coastal ecosystem in the Algarve region, with an humid area of about 100 km^2 of which one third corresponds to saltmarshes. Along its margins the Tagus estuary holds a population of about 1.6 million of total inhabitants, while the Ria Formosa supports about 136 thousand inhabitants in the three major population centres surrounding the lagoon. Both systems are vital for the local and regional economies supporting diverse activities along their margins and in their watersheds, like urban areas, industrial, port and airport facilities, fishing, tourism and aquaculture. In the Ria Formosa, salt extraction is also an important economic activity, which represents 50% of the national salt production.

The Tagus estuary and the Ria Formosa present, however, very distinct physical and morphological characteristics. One of the main differences relies on the freshwater input, which is almost negligible in the Ria Formosa, except in Tavira where the Gilão River encounters the sea. In contrast, in the Tagus estuary the mean freshwater input from its main affluent, the Tagus river, is 336 m^3/s. This difference leads to different classifications in the scope of the WFD, the Tagus estuary being classified as transitional water and the Ria Formosa being classified as coastal water. Morphologically, the two systems are also significantly different. The Tagus estuary is a single inlet system, with a narrow channel that connects to a wider inner bay, while the Ria Formosa is a multi-inlet system, with six inlets and delimited by five sandy barrier islands and two peninsulas. These different characteristics affect the circulation within both systems and, consequently, the biogeochemical dynamics.

Regarding the biogeochemical dynamics, both systems present seasonal patterns typical of temperate systems. In the Ria Formosa the water characteristics are strongly reliant, not only on seasonal variability, but also on tidal mixing, that is reflected in both spatial and short-term temporal dimensions (dependent on residence time and tidal range). The tides promote the propagation of the water masses into the lagoon and influence the physical-chemical and biological quality of the water, as well as the dynamics of the dissolved and particulate material (Falcão and Vale, 1990; Cravo *et al.*, 2014). Tides are also an important driver of the biogeochemical dynamics in the Tagus estuary, but the freshwater input also plays an important role in this system in controlling this dynamics. Residence time has been pointed out as the main factor influencing phytoplankton annual variability (Brotas and Gameiro, 2009).

Anthropogenic pressures affecting the nitrogen and phosphorus loads are typically of the same type in the Tagus estuary and the Ria Formosa, including the discharge from urban and industrial effluents and agriculture practices. However, remarkable differences are found between the Ria Formosa and Tagus estuary on the magnitude of the estimated of the nutrient loads, which are about two orders of magnitude higher in the Tagus estuary, putting in evidence the larger anthropogenic pressures in this system.

Significant variations occurred in nitrogen and phosphorous concentrations in the Tagus estuary between 1985 and 2009 (Valença et al., 2011). A "Low" nutrient quality status was proposed for this estuary (Caetano *et al.*, 2016), due to the phosphate concentrations in the upstream area. The downstream area of the estuary was classified as "High" quality and the middle estuary was identified to be at risk, due to relatively high concentrations of both phosphorus and nitrogen. Decreasing trends of nutrients concentrations since the 1970's have been found in the Ria Formosa. The highest concentrations of nutrients were found in the inner areas of the lagoon, where the water renewal is lower and the urban and agriculture inputs are more intense. The inlets and main channels of Ria Formosa, where the water exchanges are best promoted with the Atlantic Ocean, limit the impact of nutrients from anthropogenic origin and eutrophication problems (Newton *et al*., 2003; Roselli *et al*., 2013). Light is often considered as the main limiting factor for phytoplankton growth in the Tagus estuary (Gameiro and Brotas, 2010). Regarding chlorophyll *a*, both the Tagus estuary and the Ria Formosa were classified as in "High" or "Good" ecological status (Brito *et al.*, 2012a,b) and are not considered sensitive to eutrophication (Ferreira *et al.*, 2003).

The background characterization of the Tagus estuary and of the Ria Formosa performed in this report provides a better understanding of the natural variability of these systems, and of their evolution and response to anthropogenic and climate drivers. This review is also the foundation of the historical environmental data compilation that will integrate the Tagus estuary and the Ria Formosa observatories and will also support the development of the future activities of the project, namely the implementation of the numerical hydrodynamic and biogeochemical models on both systems, the anthropogenic and climate scenarios analyses and the classification.

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Appendix I

Summary of the Tagus estuary historical environmental data

Summary of the Tagus estuary historical environmental data

Dataset Title	Geographic Bounding Coordinates	Temporal Coverage	Variables	Sampling Description	Source
IBM	Three stations located along the estuary	1967-1968	Physical and biological variables, including temperature and chlorophyll *a*.	Fortnightly sampling between June 1967 and May 1968	Silva *et al.*, 1969
CEPOL	-	1970-1975	Several physical, chemical and biological variables, including nutrients	-	In Silva, 2003
EAET	Several stations covering the entire estuary and its main affluents (Tagus and Sorraia rivers)	1980-1983	Several physical, chemical and biological variables, including salinity, temperature, pH, dissolved oxygen, ammonium, nitrate, nitrite, phosphate, silicate, TSS, chlorophyll *a*.	Monthly synoptic surveys, during high tide and low tide (1980-81) Samples were collected at several depths	Martins *et al.*, 1982, 1983 Silva *et al.*, 1986
INTAGUS	Longitudinal profiles in the downstream area of the Tagus estuary (Barra-Corredor, Cala do Norte, Cala de Samora)	1988	Salinity and water temperature	Vertical sampling during high tide and low tide	Neves, 2010
VQM	Several stations covering the entire estuary, from the adjacent coastal area until Muge	1985-2009	Several physical, chemical and biological variables, including salinity, temperature, pH, dissolved oxygen, ammonium, nitrate, nitrite, phosphate, silicate, TSS, chlorophyll *a*	Sampling periodicity changed through time (six samples per year to two samples per year) Samples were collected during ebb conditions, at both bottom and surface	Valença *et al.*, 2011
FCUL_ CABRITA	Three stations covering the entire estuary, from the inlet until Vila Franca de Xira	1994-1995	Several physical, chemical and biological variables, including salinity, temperature, ammonium, nitrate, nitrite, chlorophyll *a*	Samples were collected during high tide of neap tides, at several depths	Cabrita *et al.*, 1999a
IPMA0104	Several stations covering the estuary from the inlet until Salvaterra de Magos / Valada	2001-2004	Several physical, chemical and biological variables, including salinity, temperature, dissolved oxygen, ammonium, nitrate+ nitrite, phosphate, silicate, TSS, chlorophyll *a*	Sampling in Mar/2001, Jul/2001, Feb/2004 Samples were collected during ebb conditions at several depths	Brogueira and Cabeçadas, 2006 Cabeçadas *et al.*, 2007
EEMA	Several stations covering the estuary from the inlet until Vila Franca de Xira	2009-2010	Several physical, chemical and biological variables, including salinity, temperature, pH, dissolved oxygen, ammonium, nitrate+ nitrite, phosphate, silicate, TSS, chlorophyll *a*	Three surveys (Oct/2009, Feb/2010 and Apr/2010) Samples were collected during ebb conditions, at both bottom and surface	Ferreira and Vale, 2010 Brito *et al.*, 2012a Caetano *et al.*, 2016
FCUL_ VALORSUL	Four stations covering the middle-upstream area of the estuary	1999-2016	Several physical, chemical and biological variables, including salinity, temperature, pH, ammonium, nitrate+ nitrite, phosphate, silicate, TSS, chlorophyll *a*	Monthly surveys with some gaps during the sampling period Samples were collected during ebb conditions	Gameiro *et al.*, 2007 Gameiro and Brotas, 2010 Brotas, unpublished data

EPAL	Several stations covering the estuary	2004-2016	Several physical, chemical and biological variables, including salinity, temperature, dissolved oxygen, pH, chlorophyll *a*	Sampling periodicity varied through time	EPAL, unpublished data
EPAL_ SIMTEJO	Online station located near Algés	2012-2014	Several physical, chemical and biological variables, including salinity, temperature, dissolved oxygen, pH, turbidity, chlorophyll *a*, currents	Data is acquired in continuous (with gaps during the period)	EPAL, unpublished data
EPAL_ SIMARSUL	Online station located near Montijo/Alcochete	2012-2013, 2015-2017	Several physical, chemical and biological variables, including salinity, temperature, dissolved oxygen, pH, turbidity, chlorophyll *a*, currents	Data is acquired in continuous (with gaps during the period)	EPAL, unpublished data
PREPARED_ SIGEA	Estuarine marginal area between Alcântara and Terreiro do Paço	2011-2014	Several physical and chemical variables, including salinity, temperature, pH, dissolved oxygen, ammonium, nitrate+ nitrite and phosphate	Five surveys, covering one entire tidal cycle. Samples were collected at both bottom and surface	David *et al.*, 2014, 2015 Rodrigues *et al.*, 2015
LNEC_ ALCANTARA	Online station located near Alcântara	2013-2014, 2016-2017	Several physical and chemical variables, including salinity, temperature, pH, dissolved oxygen	Data is acquired in continuous (with gaps during the period)	LNEC, unpublished data

Appendix II

Summary of the Ria Formosa historical environmental data

Summary of the Ria Formosa historical environmental data

Dataset Title	Geographic Bounding Coordinates	Temporal Coverage	Variables	Sampling Description	Source
NEIBM	Three stations covering the western zone of the lagoon	1967-1968	Temperature, salinity, chlorophyll *a*	Two monthly sampling. Samples were collected during low tide at surface level	Silva and Assis, 1970
SEP	Several stations covering the entire lagoon	1976	Several physical, chemical and biological variables, including pH, dissolved oxygen, %DO, nitrite, phosphate	Sampling in Jul/1976 in neap tide. Samples were collected during 3 complete tidal cycles at different depths	Lima and Vale, 1977
CPOL	Two stations located in the lagoon and one at sea	1978-1979	Several physical, chemical and biological variables, including temperature, salinity, dissolved oxygen, ammonium, nitrate, nitrite, phosphate, silicate, TSS	Monthly surveys from July/1978 to December/1979. Samples were collected at several depths	Benoliel, 1982
VCQA	Several stations located in the lagoon and one at sea	1980-1984	Several physical, chemical and biological variables, including temperature, salinity, pH, dissolved oxygen, %DO, ammonium, nitrate, nitrite, phosphate, silicate, chlorophyll *a*, TSS	Monthly surveys. Samples were collected at several depths	Benoliel, 1984, 1989, 1985
INIP	Several stations covering the inner area of the lagoon and 3 at sea	1982	Several physical, chemical and biological variables, including temperature, salinity, pH, dissolved oxygen, %DO, nitrate, phosphate, silicate, chlorophyll *a*, phaeopigments	Sampling in May/1982. Samples were collected during neap tide, in low and high tide	Cunha and Massapina, 1984
INIP_8485	Three stations covering the Tavira area	1984-1985	Several physical, chemical and biological variables, including temperature, salinity, pH, nitrate, nitrite, phosphate, silicate	Two monthly sampling between the period August/1984-Jan/1985. Samples were collected in low, intermediate and high tide at surface level	Falcão *et al.*, 1985
FALCAO	Several stations covering the inner area of the lagoon and some inlets	1985-1986	Several physical, chemical and biological variables, including temperature, salinity, pH, dissolved oxygen, nitrate, nitrite, phosphate, silicate, chlorophyll *a*, phaeopigments	Fortnightly sampling between September/1985 to September/1986. Samples were collected during spring and neap tide, in low and high tide	Falcão, 1996
VQM	Several stations covering the entire lagoon	1985-2009	Several physical, chemical and biological variables, including temperature, pH, %DO, ammonium, nitrate, nitrite, phosphate, chlorophyll *a*, TSS	Sampling periodicity changed through time (six samples per year to two samples per year) Samples were collected at both surface and bottom	Valença *et al.*, 2011
NEWTON	Several stations covering the entire lagoon	1987-1989	Several physical, chemical and biological variables, including temperature, salinity, %DO, ammonium, nitrate, nitrite, phosphate, silicate	Monthly surveys from June/1987 to December/1989. Samples were collected during several tidal conditions	Newton, 1995

BARBOSA	Three stations, including two located in the inner area of the lagoon and one in the inlet zone in the western sector	1988	Several physical, chemical and biological variables, including temperature, %DO, Chlorophyll *a*, phaeopigments	Sampling period during April-October/1988. Samples were collected in mid-ebb tide at surface level	Barbosa, 1989
BROCKEL	Two stations, including Ancão inlet and Esteiro do Ramalhete	1988-1989	Several physical, chemical and biological variables, including dissolved oxygen, nitrate, nitrite, phosphate, silicate	Sampling period between May/1988-Jun/1989. Samples were collected weekly, at several depths	Brockel, 1990
THIELE	Four stations covering the western area of the lagoon	1988-1989	Temperature, dissolved oxygen, Chlorophyll *a*	Sampling during the period of October/1988-November/1989. Samples were collected every two weeks at surface level	Thiele-Gliesche, 1992
CORTEZ	Several stations covering the entire western sector of the lagoon	1989-1991	Several physical, chemical and biological variables, including temperature, salinity, pH, ammonium, nitrate, nitrite, phosphate, silicate, TSS	Four surveys (Jul/1989, Feb/1991, May/1991, Oct/1991). Samples were collected at different depths	Cortez, 1992
BARBOSA	Two stations located in the western zone of the lagoon	1991-1993	Temperature, salinity, chlorophyll *a*	Sampling from March/1991 to January/1993. Samples were collected in mid-ebb and mid-flood at surface level	Barbosa, 2006
CRAVO	Two stations located in the inner area of the lagoon, close to Faro	1991-1992	Several physical, chemical and biological variables, including temperature, salinity, pH, dissolved oxygen, %DO, ammonium, nitrate, nitrite, phosphate, silicate, TSS	Sampling between April/1991 and May/1992. Samples were collected weekly at surface and bottom during low and high tide	Cravo, unpublished data
CONDINHO	Two stations located in the western zone of the lagoon	1998-1999	Several physical, chemical and biological variables, including ammonium, nitrate, nitrite, phosphate, silicate	Sampling during October/1998-October/1999. Samples were collected in high tide at surface level	Condinho, 2004
PEREIRA	Three stations covering the bridge of Faro beach, Ramalhete and Ancão inlet	2000-2002	Several physical, chemical and biological variables, including temperature, salinity, ammonium, nitrate, nitrite, phosphate, silicate	Sampling in 2000 (September, December), 2001 (March, June, September, December,) and 2002 (April, July). Samples were collected in low, mid and high water, during spring and neap tides	Pereira *et al*., 2007
LOUREIRO	Three stations covering the bridge of Faro beach, Ramalhete and Ancão inlet	2001-2002	Several physical, chemical and biological variables, including temperature, salinity, ammonium, nitrate, phosphate, chlorophyll *a*	Sampling in 2001 (June, September) and 2002 (April, July). Samples were collected in low and high water at surface level, during spring and neap tide	Loureiro *et al*., 2005
BRITO	Three stations covering the Ramalhete, Faro beach and its bridge	2006-2008	Several physical, chemical and biological variables, including temperature, salinity, %DO, ammonium, nitrate, nitrite, phosphate, silicate, chlorophyll *a*	Sampling every two weeks between April-October/2006 and March/2007-February/2008.	Brito, 2010
ALCANTAR A09	Station located in Ancão inlet	2009	Several physical, chemical and biological variables, including temperature, salinity, pH, dissolved oxygen, nitrate, nitrite, phosphate, silicate, chlorophyll *a*	One complete tidal cycle in April/2009. Samples were collected in spring tide at several depths	Alcântara *et al*., 2012

EEMA	Several stations covering the entire lagoon	2010	Several physical, chemical and biological variables, including temperature, salinity, pH, dissolved oxygen, ammonium, nitrate, nitrite, phosphate, silicate	Sampling in March/2010. Samples were collected in low and high water at surface and bottom levels	INAG, APA, 2010
OVELHEIRO	One station located in the channel of Faro beach	2010	Several physical, chemical and biological variables, including temperature, salinity, pH, dissolved oxygen, %DO, ammonium, nitrate, nitrite, phosphate, silicate, chlorophyll *a*, phaeopigments	Sampling in November/2010 during a complete tidal cycle. Samples were collected both surface and bottom levels	Ovelheiro, 2011
PONTAPE	One station located in the channel of Faro beach	2011	Several physical, chemical and biological variables, including temperature, salinity, pH, dissolved oxygen, %DO, ammonium, nitrate, nitrite, phosphate, silicate, chlorophyll *a*	Two complete tidal cycle in June and July 2011. Samples were collected at surface level	Pontapé, unpublished data
COALA	Several stations located in the western zone of the lagoon, including the three inlets and channels	2011-2013	Several physical, chemical and biological variables, including temperature, salinity, pH, dissolved oxygen, %DO, ammonium, nitrate, nitrite, phosphate, silicate, chlorophyll *a*, phaeopigments, TSS	Sampling between November/2011-July/2013 with some gaps	COALA project, unpublished data