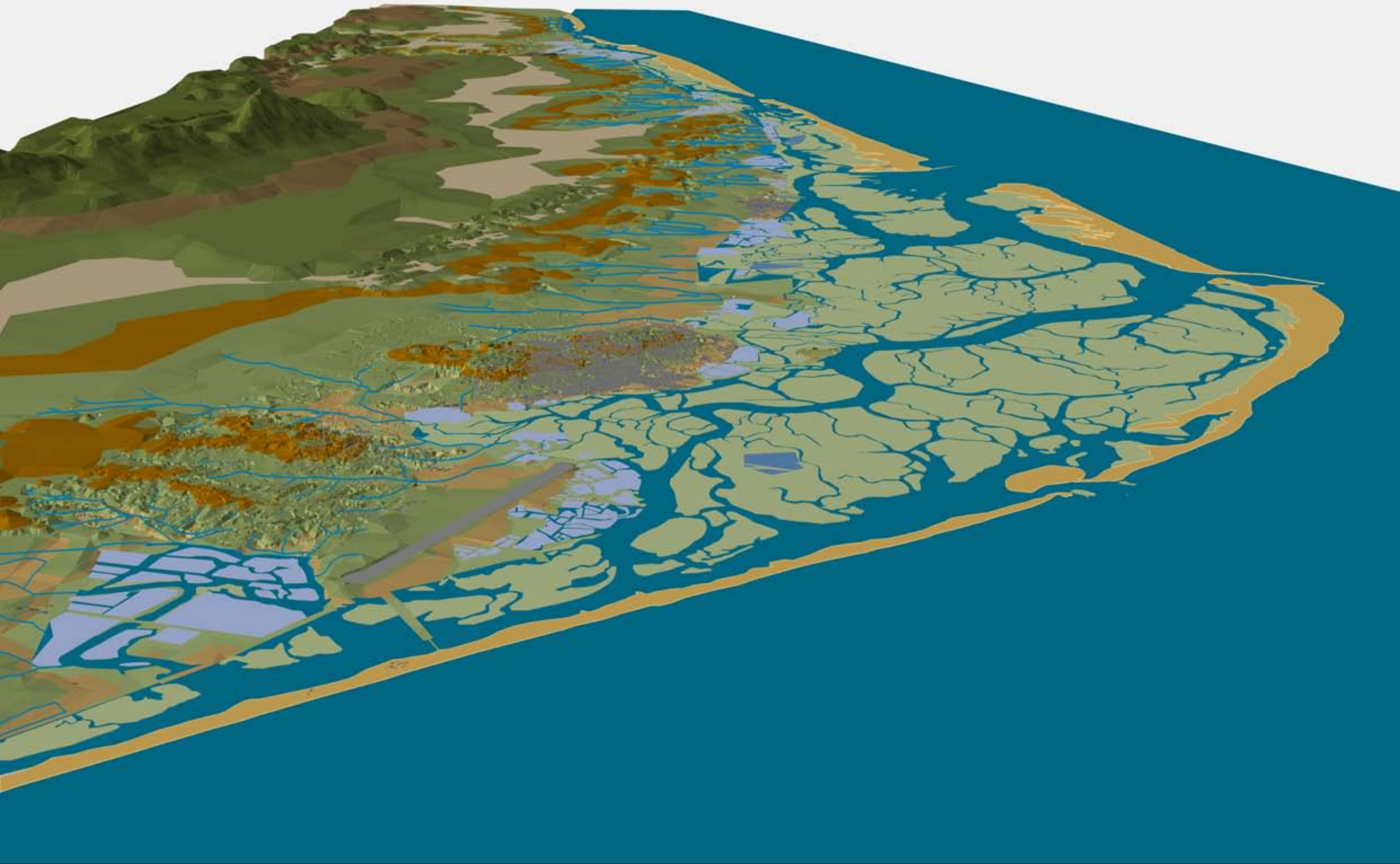

RIA FORMOSA

Challenges of a coastal lagoon in a changing environment

Edited by

Jaime Aníbal, Ana Gomes, Isabel Mendes & Delminda Moura

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Foreword

The Centre for Marine and Environmental Research (CIMA) is a multidisciplinary research centre of the University of Algarve. In addition to the scientific research and technological innovation, CIMA is involved in service delivery, graduate training and knowledge transference to the society. The CIMA researchers develop their scientific activity using a multidisciplinary approach, which contributes to produce an integrate knowledge of the ecosystems' behaviour and to understand the evolution resulting from global changes and anthropogenic impacts. These activities are developed in several territorial foci, of which the Ria Formosa is one of the most intensely studied by the CIMA researchers.

More than 60 titles of scientific papers published so far in journals of international circulation contain the designation of Ria Formosa. Many other dozens of scientific articles are also devoted to the study of the Ria Formosa barrier-island system without including this designation in the title. Dozens of master's and doctoral theses from various national and foreign universities have investigated Ria Formosa's ecology, biology, morphology, hydrodynamics, evolution and socio-economy. Thus, why CIMA decided to publish this book over the Ria Formosa? Precisely because of the intrinsic scientific value of this extraordinary wet zone located in the southern coast of the Algarve, and also several researchers of the CIMA investigate or have investigated the Ria Formosa in its multiple aspects as we can see throughout the chapters of this book.

The scientific dissemination is the main goal of this book. It synthesizes part of the scientific knowledge undertaken by various researchers allowing an integrated view of the Ria Formosa coastal lagoon.

The book does not pretend to be exhaustive, as many other works have been carried out. However, we think that readers will find information for an integrated view of the Ria Formosa coastal lagoon. We have tried to convey some of our knowledge, in a simple but scientifically correct language. This compromise is sometimes difficult to achieve. Hence, we have included in each chapter text boxes that explain the less common concepts and also a glossary at the end of the book.

Other scientists named in this book, to whom the editors and authors are grateful, have reviewed the chapters and illustrated some annexes. It is our hope that this book may contribute to the dissemination of the scientific knowledge, which is a common objective of the University of Algarve and the Centre for Marine and Environmental Research (CIMA: http://www.cima.ualg.pt/).

Editors

Preface

Miguel Marques

Economist, Specialist in Marine Affairs

This book entitled "RIA FORMOSA. Challenges of a coastal lagoon in a changing environment" is an astonishing exercise of disclosing the main challenges of Ria Formosa, a vital lagoon for the Algarve Region and for Portugal as a whole.

Coastal interface areas between sea and land are very important, rich, sensitive and extremely dynamic areas. There are multiple and complex changes that, either by nature or by human action, occur in coastal zones, from erosion to silting phenomena, from changes in currents to floods ...

This lagoon system, protected by barrier-islands with dunes, is the support of relevant economic activities. Apparently, these barrier-islands were born in the sea and are in permanent movement, towards the continent. The movement is visible, within a decade, there are areas of sand that are decreasing dangerously and others to gain more sand.

The example of the Ria Formosa reminds us of the need for any planning of activities, industrial or non-industrial, using the coastline should always keep in mind the respect for the environment and should foresee, as far as possible, the physical dynamics that the natural marine resource will have in the future. Failure to take account of the high probability of changes in the coastline, motivated by nature or human beings, means that there may be considerable economic, social and environmental damage that can be avoided.

Congratulations to the authors of this book, that invested their time and deep knowledge to bring to light relevant challenges that Ria Formosa faces and suggestions to overcome the identified risks. The need to implement specific integrated procedures devoted to the management of the back barrier shores. The understanding of the interconnectivity between the lagoon and the sea that does not depend exclusively on tides but also on other driving forces acting on the coast, such as wind and associated oceanographic processes, either inner countercurrent or upwelling. The importance of the use of mathematical modelling of waste water plumes is a tool that enables the prediction of water quality. The continuous observation of microorganism's activity enabled by the development of epifluorescence microscopy and sensitive radioisotope techniques is key. The intertidal areas of Ria Formosa are systems with low Ulvales herbivory, meaning that they are not top-down controlled. Phytoremediation on wetlands can be considered an important type of eco-services to society, based on 'green' technologies and low energy consumption. The presence of hazardous substances such as metals, persistent organic compounds, and polycyclic aromatic hydrocarbons and emerging contaminants including personal care products and pharmaceutical compounds is a cause of concern for the sustainability of the lagoon. The opportunity to test a floatable tidal energy converter at the lagoon and the application of remote sensing for monitoring the Ria Formosa is shown in this book.

One of the most important lessons I have learned in my many travels around the world to analyse human development across the ocean is that this resource is much less homogeneous than it seems. Each point in the sea is different (in terms of temperature, depth, currents, nutrients ...). In this context, it is fundamental to study very well all the physical characteristics of the sea in order to be able to develop, in a sustainable way, this fantastic resource. This book is a fundamental contribution to the sustainable development of the oceans, not only because it studies very well the specific characteristics of a place, but also because it analyses in an integrated way the multiple challenges that blue growth has to face in the future.

1. Introduction

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Ria Formosa is one of the most important weatlands of the Portuguese territory. Its rarity and ecological value led to the creation of the Ria Formosa Natural Park (law-Decree 373/87, 9th December). Ria Formosa hosts a remarkable diversity of habitats and biodiversity. It is of fundamental importance for several species of migratory birds and, some species in decline find here the optimal conditions for nesting. This is the case of the species *Porphyrio porphirio* that is the symbol of the Ria Formosa Natural Park. Due to protective measures of this species, its population has increased in recent years.

The natural system named Ria Formosa is a shallow coastal lagoon (average depth of 2 m) protected from the direct impact of marine waves by a barrier-island system formed by five islands and two peninsulas facing the sea along ca. 55 km (Figure 1.1). The Ria Formosa barrier islands are narrow and elongated morphosedimentary features that diverge NW and NE orientated from the Cape St. Maria (Figure 1.1). St. Maria de Hárune, later on renamed as St. Maria de Fárão, were the names of the city of Faro, after the Arab domination, during which was Ibne-Hárune (Guerreiro and Magalhães, 1983). The lagoon with extensive marshes and tidal channels (total area of 18000 ha) maintains connections with the sea through six inlets, which guarantees daily renewal of water and nutrients at the pace of tides.

The maintenance of efficient inlets is of fundamental importance for the biodiversity and ecosystem services preservation. Due to the highly dynamic of the hydrosedimentary processes, the inlets tend to migrate eastward drived by the alongshore drift. This was why the Ancão and Fuseta inlets were relocated. At the east and west ends, the barrier-island system connects with the mainland through two peninsulas (spits), respectively the Cacela and Ancão peninsulas. The remarkable morho-hydrodynamism of the overall system, is also expressed on the landward migration of the backbarrier provoking a shrinking of the lagoonal area (e.g., Andrade et al., 2004; Ferreira et al., 2016; Kombiadou et al., 2018). Dunes are important forms of the Ria Formosa, which sedimentary dynamic is the main mechanism for the barrier-islands evolution (Ferreira et al., 2016).

One of the great questions about the barrier-islands of the Ria Formosa lagoon, is the origin of such amount of sand necessary to form them. Even today the source of the sands remains open. The fluvial origin of the sediments is discarded since there are no important rivers that flow to the system (Dias et al., 2004; Andrade et al., 2004). However, in the geological past, the rivers and streams, had different shapes and sizes from what we are observing today. Thus, some of the sand of the barrier islands can be inherited from those distant times thereafter reworked by waves and currents. The scarcity of fluvial sediment contribution is one feature that distinguishes the Ria formosa from other coastal lagoon worldwide. In addition, those low fluvial inputs combined with the groundwater discharges into the lagoon and the high rate of water renewal through the inlets are responsible for the high values of salinity of the lagoonal water (mean salinity = 35.25 g/kg; Newton and Muge, 2003) and for other chemical characteristics of the system (Bebianno, 1995; Andrade et al., 2004; Leote et al., 2008).

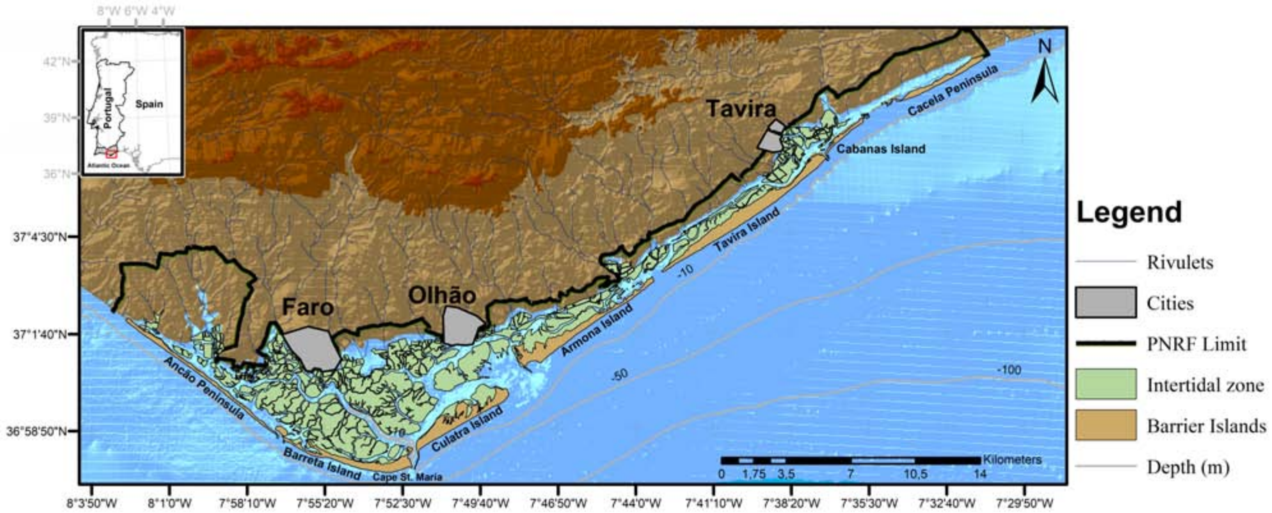

Figure 1.1.
Ria Formosa lagoon and barrier island system (Credits: Sónia Oliveira).

Regardless the questions about the source of the sand that forms the barrier islands, the most accepted conceptual model of the genesis of the Ria Formosa, points the mean sea level rise as the main forcer (e.g., Pilkey et al., 1989). During the Last Glacial Maximum (LGM) ca. 18000 years ago, the mean sea level was 120 m lower than the present. Several sandy bodies roughly parallel to the past coastline were formed and migrated landward to form islands, as the mean sea level rose after the LGM. Those islands reached their current position ca. 7000 years ago (Sousa et al., 2014; 2018) (Figure 1.2). Since then, the barrier morphology and evolution were mainly controlled by waves, tides, extreme events (e.g., storms and tsunami) and mean sea level rise.

Barrier islands are among the most vulnerable natural systems to the mean sea level rise, extreme events, and anthropic activities. In this way, a sustainable coastal management is required to mitigate these effects. The Ria Formosa lagoon has been a very attractive area for human occupation, since the Paleolithic period, due to mild conditions, and living and non-living resources availability. While the first settlements in the 19th and early 20th centuries were fishermen, since the 1960s the increasing occupation by buildings and parkings have contributed to the sedimentary imbalance of the barrier island system. This situation is particularly worrisome at the Faro beach, peninsula of Ancão (Ceia et al., 2010).

Beaches, dunes and marshes lead to different habitats therefore to high biodiversity in the Ria Formosa. A high percentage (ca. 90%- Andrade et al., 2004) of the lagoon area is composed by intertidal morphosedimentary forms (Figure 1.1). According to the elevation of these forms, the environmental variables such as sediment, salinity, thermal amplitudes, insolation and time of submergence are quite different determining a well defined phytozonation (Arnaud-Fasseta et al., 2006; Oliveira, 2014).

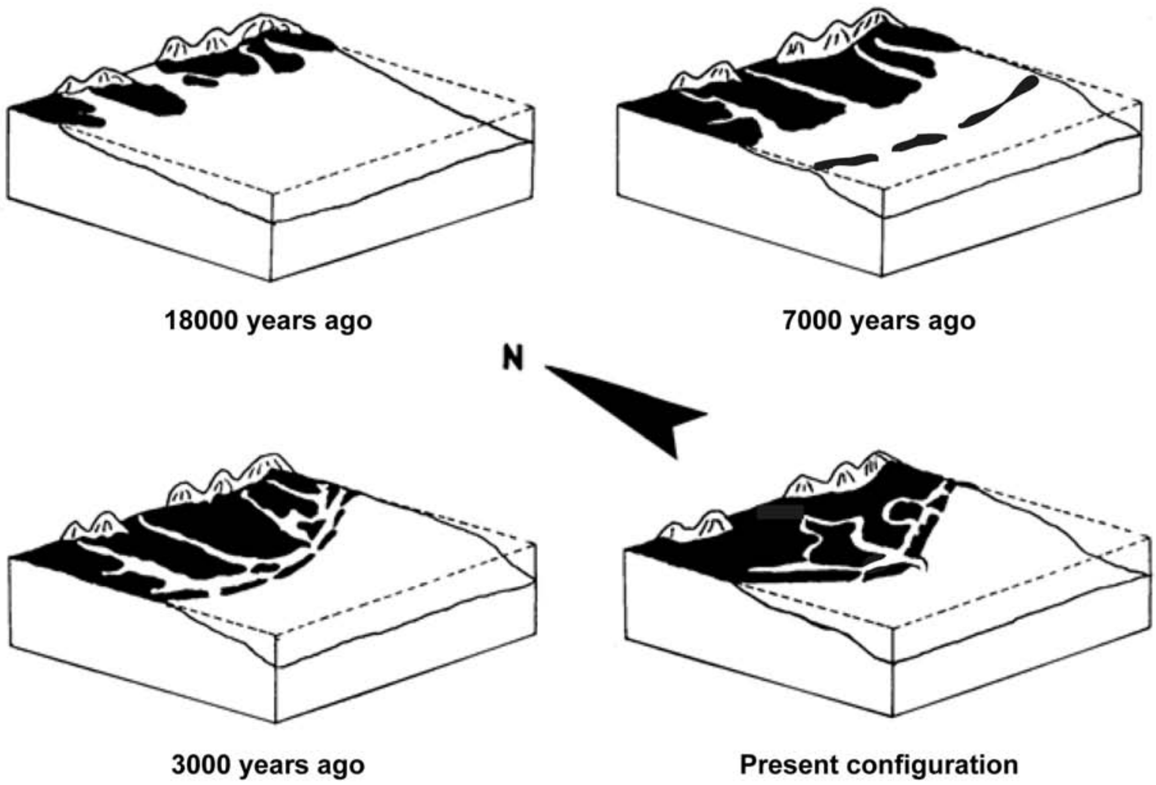

Figure 1.2.
Conceptual diagram of the evolution of the Ria Formosa lagoon.

The ecological, morphological, hydrological and socioeconomic values of the Ria Formosa lagoon are dynamically interconnected (see http://www.cima.ualg.pt/cimaualg/index.php/pt/ciencia-para-a-sociedade/aplicacoes-didaticas) and will be further explored along this book.

References

Andrade, C., Freitas, M.C., Moreno, J. & Craveiro, S.C., 2004. Stratigraphical evidence of Late Holocene barrier breaching and extreme storms in lagoonal sediments of Ria Formosa, Algarve, Portugal. *Marine Geology*, 210 (1-4), 339-362. https://doi.org/10.1016/j.margeo.2004.05.016

Arnaud-Fasseta, G., Bertrand, F., Costa, S. & Davidson, R., 2006. The western lagoon marshes of the Ria Formosa (Southern Portugal): Sediment-vegetation dynamics, long-term to short-term changes and perspective. *Continental Shelf Research* 26, 363-384. https://doi.org/10.1016/j.csr.2005.12.008

Bebianno, M.J., 1995. Effects of pollutants in the Ria Formosa Lagoon, Portugal. *The Science of the Total Environment*, 171, 107-115. https://doi.org/10.1016/0048-9697(95)04672-9

Ceia, F.R., Patrício, J., Marques, J.C. & Dias, J.M., 2010. Coastal vulnerability in barrier islands: the high risk áreas of the Ria Formosa (Portugal) system. *Ocean & Coastal Management* 53, 478-486. https://doi.org/10.1016/j.ocecoaman.2010.06.004

Dias, A., Ferreira, Ó, & Moura, D., 2004. Livro Guia da Excursão: II Reunião Científica da Rede CYTED-XVII /3º SIPRES, Interdisciolinary Symposium on wetlands, Faro, Maio, 2004, 18p. Available in: http://w3.ualg.pt/~jdias/JAD/papers/xOP/04_Humedales.pdf

Ferreira, Ó., Matias, A. & Pacheco, A., 2016. The east coast of Algarve: a barrier island dominated coast. *Thalassas*, 32 (2), 75-85. https://doi.org/10.1007/s41208-016-0010-1

Guerreiro, M.V. & Magalhães, J.R., 1983. Duas Descrições do Algarve no Século XVI. In: Sá da Costa (Edit.), Lisboa, 46 p.

Kombiadou, K., Matias, A., Carrasco, R., Ferreira, Ó., Costas, S., & Vieira, G., 2018. Towards assessing the resilience of complex coastal systems: exemples from Ria Formosa (south Portugal). *Journal of Coastal Research*, SI 85, 646-650, https://doi.org/10.2112/SI85-130.1

Leote, C., Ibánhez, J.S. & Rocha, C., 2008. Submarine Groundwater Discharge as a nitrogen source to the Ria Formosa studied with seepage meters. *Biogeochemistry*, 88 (2), 185-194. https://doi.org/10.1007/s10533-008-9204-9

Newton, A. & Mudge, S.M., 2003. Temperature and salinity regimes in a shallow, mesotidal lagoon, the Ria Formosa, Portugal. *Estuarine, Coastal and Shelf Science*, 57 (1-2), 75-85. https://doi.org/10.1016/S0272-7714(02)00332-3

Oliveira, S., 2014. Incorporação de software multimédia e de informação em sistema de informação geográfica: o exemplo da aplicação didática ForDid (Ria Formosa). Trabalho de Projecto do Mestrado em Geomática, Ramo- Análise de Sistemas Ambientais, Universidade do Algarve, 114 p. Available in https://sapientia.ualg.pt/.../UALG_Sonia_O%20exemplo%20da%20aplicação%20didát...

Pilkey, O.H., Neal, W.J., Monteiro, J.H. & Dias, I.A., 1989. Algarve barrier islands: a noncoastal- plain system in Portugal. *Journal of Coastal Research*, 5 (2), 239-261.

Sousa, C., Boski, T., Gomes, A., Pereira, L. Lampreia, J. & Oliveira, S., 2014. Holocene reconstruction of the Ria Formosa coastal lagoon (south Portugal) based on a pre-Holocene paleosurface digital model. *Comunicações Geológicas* 101, Especial I, 635-639. http://www.lneg.pt/iedt/unidades/16/paginas/26/30/185

Sousa, C., Boski, T. & Pereira, L., 2018. Holocene evolution of a barrier island system, Ria Formosa, South Portugal. *The Holocene*, 1-3. https://doi.org/10.1177/o959683618804639

2. Backbarrier shores along the Ria Formosa lagoon

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2.1. Low-energy environments and backbarrier shores: where can we find them?

Low energy beaches are located in sheltered and fetch-limited environments. The *fetch*, also called the fetch length, is the uninterrupted distance over the sea surface for which the wind can blow without a change in direction and affects the growth of wind-waves. Fetch-limited beaches are found in estuaries and bays (e.g. Chesapeake Bay, USA), behind ocean barriers (e.g. Pamlico Sound, USA), adjacent to inlets (e.g. Tapora Bank, New Zealand), deltas (e.g. Menderes River, Turkey), eroding thermokarst (e.g. Yensei Bay, Russia), and glacial outwash fans (e.g. Canal Baker, Chile; Cooper et al., 2007). In the case of barrier island systems, the back of barrier islands facing the lagoon environments i.e., backbarrier shores are fetch-limited environments.
A barrier is an elongated ridge that is composed predominantly of unconsolidated sand and/or gravel and protect the adjacent mainland from open-water processes (Figure 2.1). From the sea to the mainland, the barriers are generally composed of the shoreface, dune and backbarrier environments, and they are separated alongshore by tidal inlets (Figure 2.1). Barrier islands are dynamic systems, constantly on the move, migrating under the influence of waves, tides, currents, storms, and changing mean sea levels. The backbarrier is a narrow, elongated, intertidal landform that is located on the lagoon or estuary side of the barrier island and can take the form of sandy beaches, tidal flats or salt marshes (Figure 2.1). Backbarrier beaches tend to be morphodynamically reflective (according to the classification of Wright & Short, 1984), with steep narrow foreshores that have smaller seasonal variations than open ocean beaches. The tidal flat is bound to the foreshore and might end in a salt marsh fringe. Salt marshes are among the most productive ecosystems on earth. Backbarriers provide critical ecosystem services to coastal populations (see Box 2.1.).

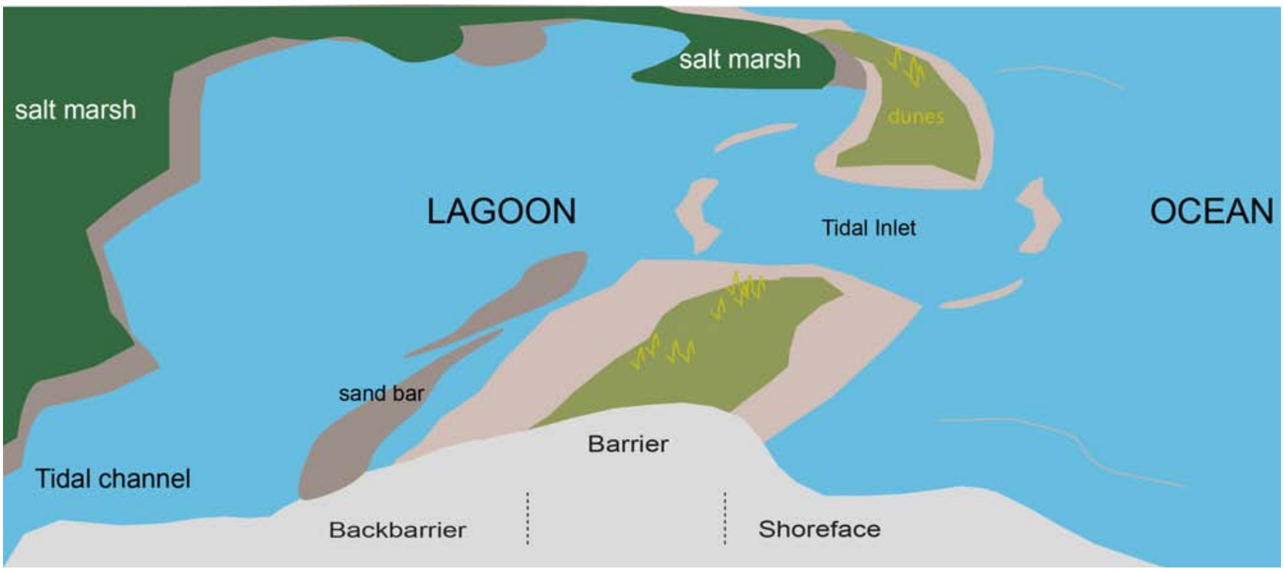


Figure 2.1.
View of barrier islands major compartments.

Box 2.1. Backbarrier ecology: the importance of salt marshes

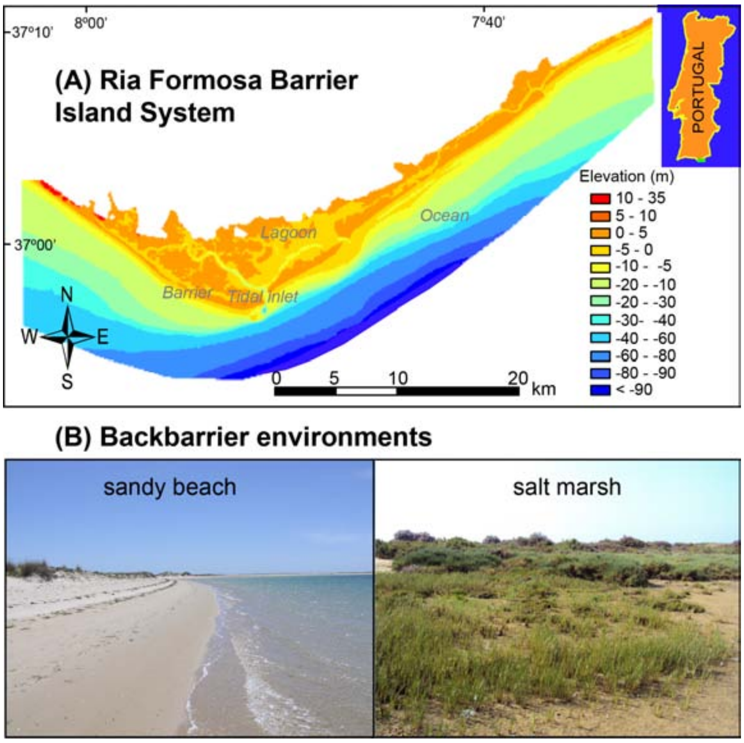
Salt marshes are among the most productive ecosystems on earth and have great ecological value, namely in flood risk management and erosion, nutrient regeneration, primary production, habitat for wildlife species, and as shoreline stabilizer (e.g. Costanza et al., 1997; Caçador et al., 2016). Salt marshes ecological role have been formally recognised by its inclusion in the Water Framework Directive.
Over time, salt marshes accumulate organic material, forming a dense layer called peat. Salt marshes and tidal flats also play an important role in capturing carbon (especially *Zostera noltii* tidal plains in Figure 2.2), by absorbing in biomass the gaseous carbon – carbon dioxide. Carbon fixation in the soil is highly beneficial to slow global warming and other harmful effects of high carbon content in the atmosphere. When a marsh is destroyed, usually because of human impact, and the organisms die, the carbon that had been absorbed and stored in the biome will be released back into the air as carbon dioxide.

Figure 2.2.
View of the ecological marsh succession, from the low marsh dominated by *Spartina maritima* and the tidal flat dominated by *Zostera noltii* (in the Culatra Island backbarrier; photo by A. Rita Carrasco, 2017).

2.2. Ria Formosa backbarriers

The Ria Formosa is a highly dynamic multi-inlet barrier island system located in the Algarve region, Southern Portugal (Figure 2.3). The Ria Formosa backbarrier forms a continuum system, ranging from linear sand bodies morphologically indistinguishable from transgressive open-ocean barriers (Pilkey et al., 2009) to extensive fans of tidal marshes, intercepted by very small tidal channels.
The entire Ria Formosa lagoon covers an area of 8.4×10^7 m^2 (Andrade, 1990), and is characterised by i) extensive salt marsh areas, with a dense distribution of shallow meanders composed of silt and fine sand (Bettencourt, 1994); ii) large sand flats, partially flooded and reworked during spring tides (Pilkey et al., 1989); and iii) a complex network of natural and partially-dredged channels, which get narrower and shallower towards the upper regions of the system (Andrade et al., 1998). The lagoon is a very shallow area with a maximum depth of 2 m (below mean sea level, Figure 2.3), supporting substantial sedimentary and morphological variability (Andrade, 1990).

Figure 2.3.
(A) Ria Formosa barrier system (coordinates WGS84; elevation referred mean sea level).
(B) View of the two main environments in the backbarrier shores, namely sandy beaches and salt marshes (photos by A. Rita Carrasco, 2017).



The barrier system comprises five islands and two peninsulas, separated by six tidal inlets. The barrier system is extremely dynamic which has been related with tidal inlet evolution (Pacheco et al., 2010; Vila-Concejo et al., 2006), shoreline evolution (Garcia et al., 2002), longshore drift (Ciavola et al., 1997), overwash processes (Matias et al., 2008), dune formation (Gomes et al., 1994), backbarrier processes (Carrasco et al., 2011) and artificial nourishment actions (Dias et al., 2003).
The backbarrier system receives minimal ocean swell and is dependent on local winds for wave development. Most backbarrier shores face fetch distances shorter than 2 km (see example Figure 2.4A), and therefore they are exposed to small waves and are characterised by low, narrow sandy beaches (Figure 2.4B), alternating with portions of tidal flats, salt marshes, and washover plains (flat areas generated by large overwash events and breaches). Occasionally, intertidal bars are attached to the beach foreshore (sand banks in Figure 2.4C), suggesting that there is sediment exchange between the low-tide terrace and the foreshore (see beach segmentation in Figure 2.4D).
Evolutionary trends calculated from historic aerial photograph analysis show that the extremities of the system (both peninsulas) are immature (recent and under construction), while the rest of the system is characterised by a predominance of mature backbarriers (Carrasco et al., 2008). The overall evolutionary trend of the Ria Formosa backbarrier indicates a shrinking of the lagoon (coastal squeeze) due to the landward displacement of the backbarrier together with a decrease in the extent of the backbarrier coastline (Carrasco et al., 2008).
From the view point of conservation, the Ria Formosa lagoon was designated a Natural Reserve in 1978, a Natural Park in 1987, and is now part of the Natura 2000 network, with the aim of achieving a rational and sustainable exploitation of its resources (see Box 2.2.). The system hosts high faunal diversity, with national importance as a nest-building zone and international relevance for bird migration. Moreover, it is considered a worldwide noteworthy wetland area, protected by the RAMSAR and BERNA conventions. Ria Formosa resources protection and exploitation involves a complex web of cultural habits, economic constraints, and legal and political perceptions, amongst other issues, making management a difficult task.

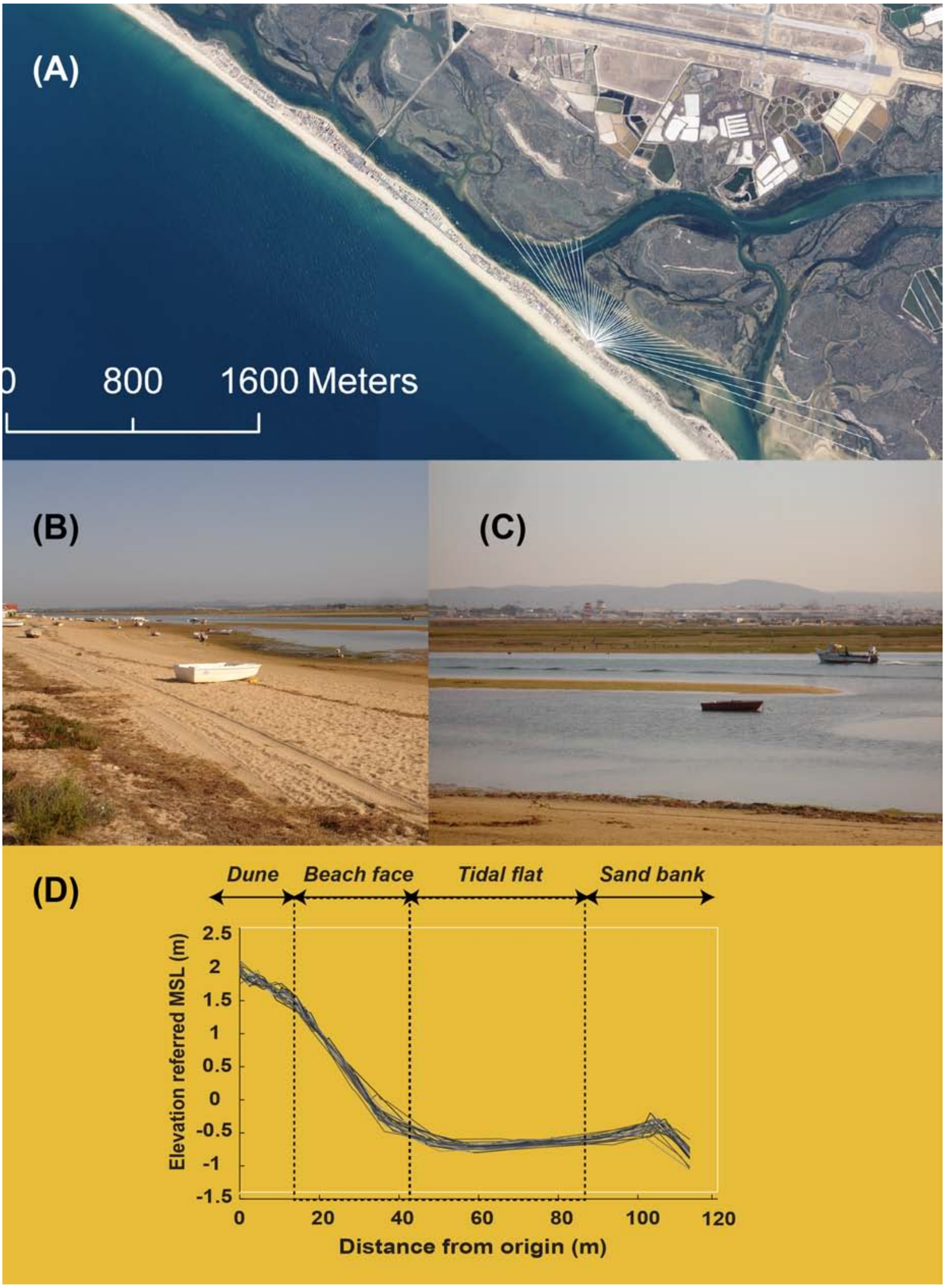


Figure 2.4.
(A) Example of fetch distribution behind Praia de Faro;
(B) view of the foreshore (dune and beach face, photos by A. Rita Carrasco, 2008);
(C) view of an intertidal bar attached to the tidal flat (sand bank);
(D) example of a typical profile segmentation in sandy backshores at Ancão Peninsula backbarrier composed of dune, beach-face, tidal flat and sand bank.

Box 2.2. The importance of the Ria Formosa backbarrier and lagoon to the local economy

Besides being an important element of the overall coastal system, the backbarrier and lagoon serve as the main 'feeder' of the local marine economy, with economic activities such as aquaculture, fishing, shipping, sand mining and tourism, coexisting in a fragile and often-competing combination. The shellfish and clams harvest, which takes place in most of the backbarrier shores and inside the lagoon, is the most important addition to the local economy as they are a high-value crop, representing more than 90% of the national clam harvest. It is estimated that about 5000 people depend on the clam industry, out of the about 100,000 people total population around the lagoon (Cristina et al., 2006). Urban development in the Ria Formosa backbarrier is concentrated in 5 villages, namely Praia de Faro, Farol, Hangares, Culatra e Armona (Figure 2.5).

Figure 2.5.
Example human development and activities on the backbarrier of Culatra Island (photo by A. Rita Carrasco, 2006).

2.3. Morphological Evolution

Backbarrier beach profile characteristics include a narrow foreshore (~35 m wide, slope $\cong$ 0.07), with reflective swash zones and a low gradient terrace acting as a wave energy filter (Figure 2.4 (B) and (C)). The tidal flat has a gentle slope (slope $\cong$ 0.01; Figure 2.4 (C) and (D)), ending in a small flat parallel sand bank (30 m of length, slope $\cong$ 0.06). The tidal flat is mainly sandy (mean grain size, dmean = 0.3 mm) with 9 % of mud. The beach face and sand bank are coarser (dmean of 0.9 mm and 0.4 mm, respectively).
Site-specific factors related to geomorphologic settings and hydrodynamics, for example the proximity to a tidal inlet, shape beach evolution. Backbarrier beaches face almost the same forcing mechanisms as

oceanic beaches, but at a relatively lower magnitude (Figure 2.6). For instance, wind and wave-setup are much reduced in backbarrier beaches, when compared with wind and wave-setup acting on oceanic beaches; wave-runup is almost null in backbarrier beaches (Figure 2.6).

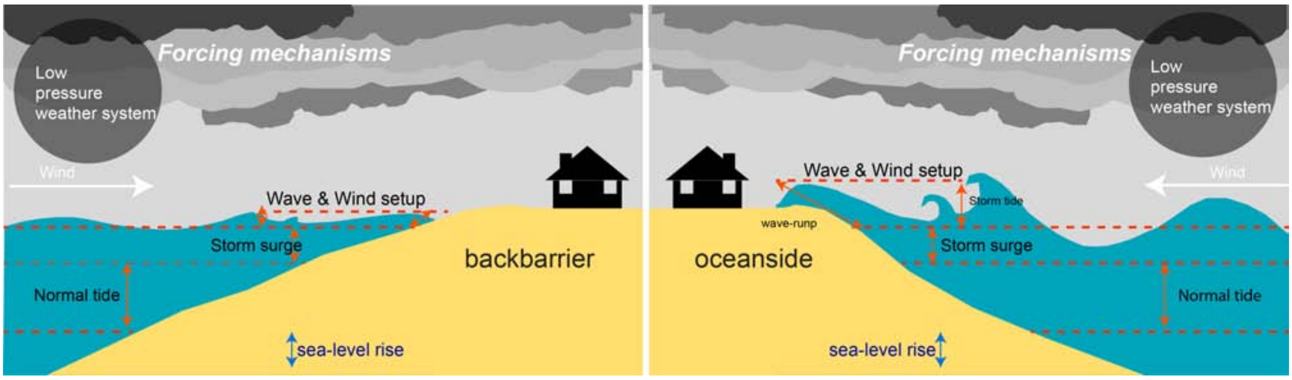


Figure 2.6.
Comparison between forcing mechanism action in oceanic beaches and backbarrier beaches.

Medium time-scale analysis (days to years) demonstrates that volumetric beach response is slow and continuous (less than tens of cubic meters of change between months), similar to other sheltered mesotidal beaches described in literature (Carrasco et al., 2012; Figure 2.7A and B). Short-term dataset analysis (minutes to days) confirmed the limited sediment transport, with daily rates of change below 0.05 m^3/m, occurring mostly on the beach face (see example Figure 2.7B). The beach face and the nearshore (sand bank) act as independent morphological sub-systems. Contrary to most oceanic beaches, backbarrier beaches lack cyclic changes, with a slow response to hydrodynamic forcing (Figure 2.8).

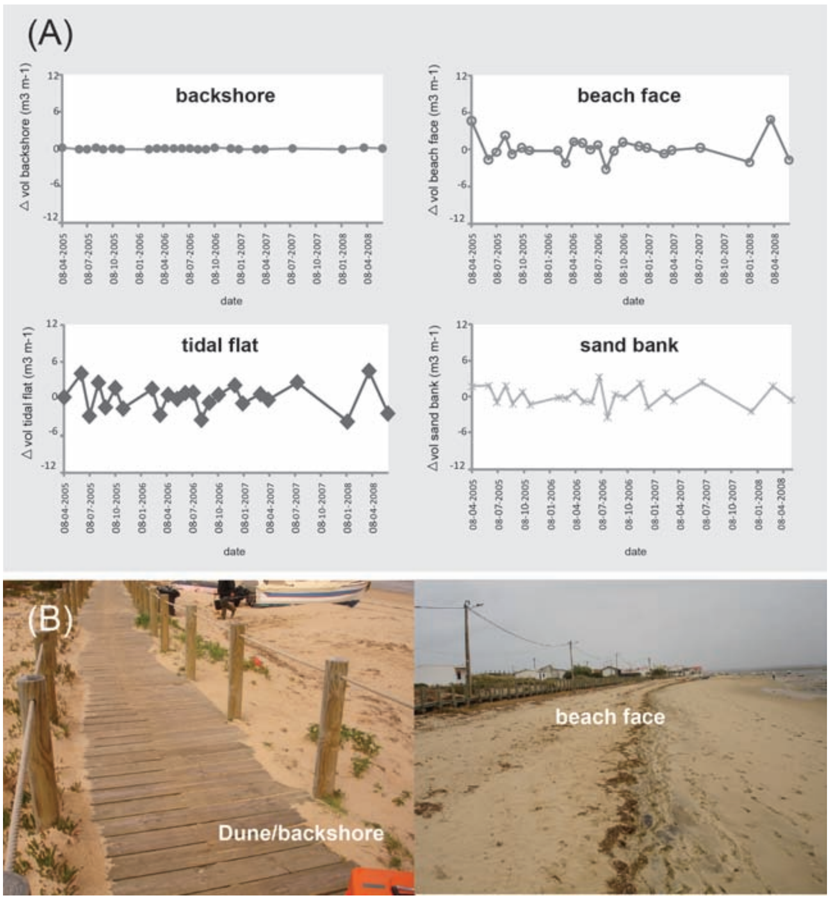


Figure 2.7.
(A) Volumetric variations at the backshore, beach face, tidal flat and sand bank zones, over two years of analysis in a backbarrier portion of Ancão Peninsula (datasets from BERNA project, financed by Fundação para Ciência e Tecnologia under reference POCTI/CTA/45431/2002);
(B) sand accumulation in the backshore driven by wind, and embryonic berm formation as result of wind-induced waves (associated to relative higher energetic conditions or storm conditions; photos by A. Rita Carrasco, June 2006 and February 2008, respectively).

2.3.1. *Wind, waves and tidal currents on the backbarrier beaches of Ria Formosa*

Since most backbarriers of the Ria Formosa are nearby- or under the direct influence of tidal channels and inlets, the tidal currents are the principal source of energy for sediments mobilization and transport (Carrasco et al., 2011). Average local tidal currents are within the order of 0.3 m/s, with maximum velocities of 0.5 m/s; these values are closely dependent on the distance to inlets. Backbarrier beaches are not very reactive to wind intensity fluctuations and the sand availability is an important factor for beach modulation. Figure 2.8 shows the lack of correlation between beach morphological changes and wind variability (Figure 2.8; Carrasco et al., 2012). During relatively high-energy events (e.g. winter), mudflats can even prevent most waves from reaching the barriers and reduce the energy of the few waves that reach the shore (as suggested by Lewis et al., 2007); other factors as wakes present minor influence to morphology (see Box 2.3.). Wakes are small waves generated by the passage of boats on channels.

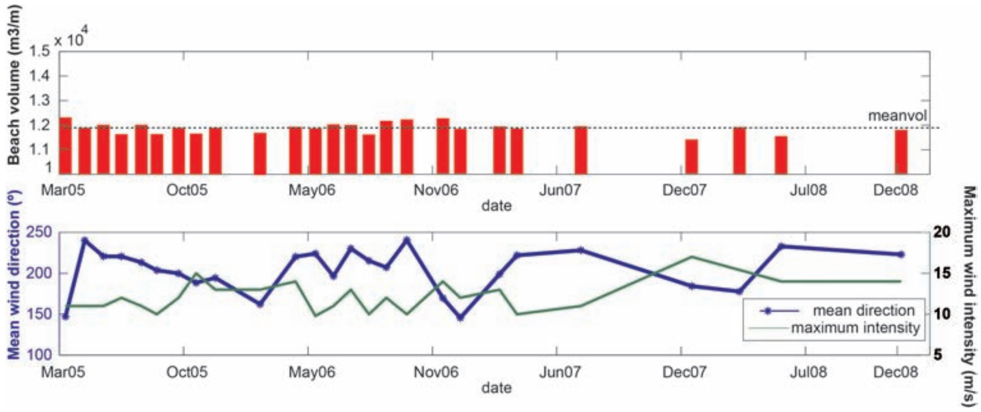


Figure 2.8.
Example of beach volume variations at a backbarrier beach exposed to N-NE winds, in comparison with changes in the local wind patterns (wind direction and wind intensity); dashed line represents the averaged beach volume during three years of analysis.

Box 2.3. Do you know that…

The generation, propagation, attenuation and forces related to boat generated wake waves are being recently investigated due to increasing concerns regarding their impact on backbarriers beaches and salt marshes. Boat wakes have been shown to have erosive effects on shorelines (e.g. Ellis et al., 2002), scour the bottom of the shoreface, and temporarily decrease of water clarity (Kurennoy et al., 2011). In addition, boat wake impacts include vegetative damage and disruption of faunal communities. They are most destructive in shallow and narrow waterways because wake energy does not have the opportunity to dissipate over distance. Numerous waves within these ranges were documented in the Praia de Faro backbarrier and all around the lagoon, especially inside the main navigational channels.

2.3.2. The role of human interventions on the backbarrier shores

Permanent or seasonal human modifications, such as urban development or marine exploitation, are conspicuous on many backbarrier shores in the world (Nordstrom et al., 1996). Many human-altered beaches around the world bear little resemblance to their potential state under natural conditions, and many others were created where none would occur naturally. There are numerous types of impacts, and several have profound effects for many years, for instance, natural sediment deposits in backbarrier marshes, tidal creeks or other lagoon environments, behind barrier islands and spits, have been used in the past for beach nourishment. Dredging operations have removed sediments inside the lagoons, with consequences to the sediment supply of backbarrier shores. This occurred during the last years in the Ancão Peninsula backbarrier, where a dramatic morphological change is noticeable between 1947 and ~2007 (Figure 2.9). The main reasons for the observed changes are artificial operations to manage the Ancão Channel. The dredging of Ancão Channel after 1976 and the relocation of Ancão Inlet in 1996, lead to a shoreline advance (i.e. backbarrier shoreline displacement towards the lagoon), development of a detached morphology (sand bank, Figure 2.9), while the channel reduced its width and its margins enlarged (development of a tidal flat). Human activities left a strong local imprint and consequent inheritance, instilling morphological changes that were neither erased nor counteracted by the cumulative backbarrier evolution trends (Figure 2.9).

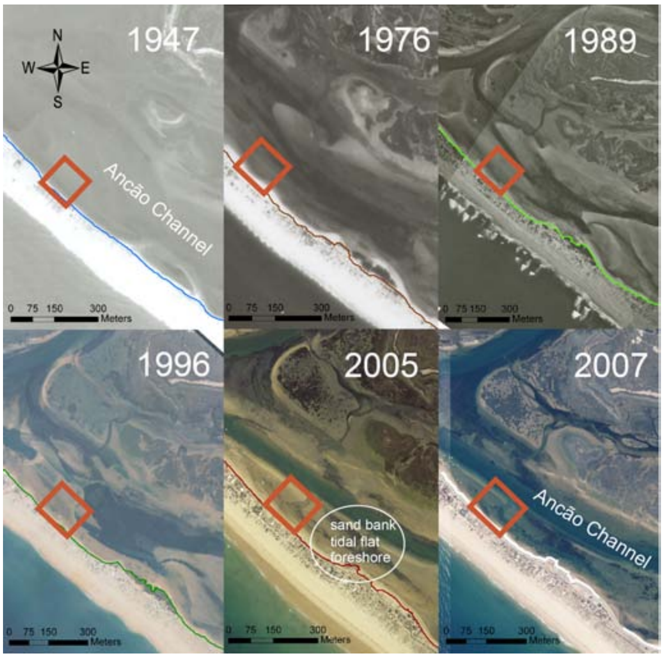


Figure 2.9.
Aerial views of long-term evolution of the Ancão Peninsula backbarrier (aerial photos from CIMA/UAlg database). Inside the red square, from 1947 to 2007, a sandy platform developed, that differentiated trough time into three sandy morphologies: foreshore, tidal flat and sand bank.

2.3.3. The role of sea-level rise in the sedimentary processes of backbarriers

Although the overall understanding of how barrier islands respond to climate change continues to improve, very few details are known about how the backbarrier shores will evolve to rising sea levels (Carrasco et al., 2016), including the behaviour of Ria Formosa under sea-level rise. Literature predicts that under such conditions, backbarrier shores will lose sub-areal extent and the sea-level rise will gradually change the hypsometry of the barrier, transforming supratidal areas into intertidal and open-water environments. Inside the lagoons, the inundation of the tidal flats and salt marshes will probably increase, leading to the conversion of sub-areal areas on backbarrier to open waters (Carrasco et al., 2016). Backbarriers composed of salt marshes, appear to be less vulnerable to rising sea level because marsh can accommodate vertical accretion up to a certain rate (Carrasco et al., 2016; see Box 2.4.), although results are not conclusive.

On the frontier with ocean, sea-level rise may cause changes in inlets geometry or in tidal forcings (Smith, 2001), affecting the baseline level of sediment transport arising to backbarrier shores. It is still, however, difficult to make accurate predictions of coastal change due the non-linearity of sedimentary processes, and the uncertainty on their 'downscaling'. Even if detailed descriptions exist of the responses of barrier chains and inlets to sea-level rise, as well as various attempts to systematize the foreseen impacts, a deficiency remains in the conceptualization of expected morphological changes.

Box 2.4. The role of seagrass in the long-term sedimentary processes of backbarrier salt marshes

Seagrass meadows (see Figure 2.10) can stabilise sediments and help to facilitate surface elevation accretion (Fonseca, 1996). When seagrass occupies the entire water column, current velocities are reduced, and sediments tend to accumulate.

The impact of seagrasses is remarkably strong, with average sediment accumulation differences up to 30 mm per year between seagrass and unvegetated areas (e.g. Potouroglou et al., 2017). The capacity of seagrasses for balancing the deposition of suspended sediment and resuspension is highly dependent on the development stage and health of the plants, as well as local hydrological conditions.

Figure 2.10.
Example of seagrass plain in the Culatra Island backbarrier (photo by A. Rita Carrasco, 2017).

Figure 2.11 summarizes the main drivers and respective timescales of interaction, acting on the backbarrier shores of Ria Formosa. Tidal currents, wind and wind-induced waves, rising sea level and human interventions, are the main natural and anthropogenic forcing mechanisms that drive changes at backbarrier shores (Figure 2.11). Each driving factor operates at different timescales; for instance, human interventions affects the short- to long-term evolution of backbarrier shores, whilst the tidal currents, but at the long-term their effect can be counteracted.

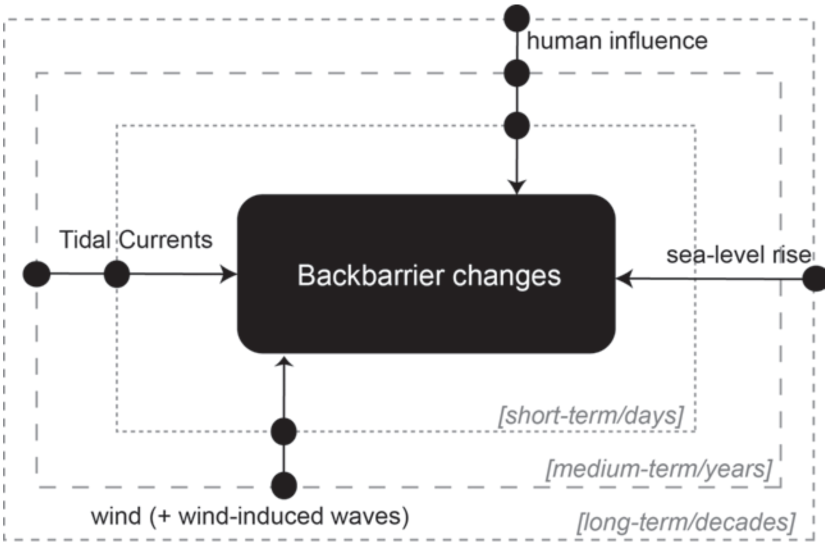


Figure 2.11. Summary of the main drivers and respective timescales acting on the backbarrier shores of Ria Formosa.

2.4. Coastal management and ecosystem-based approach

Although the Ria Formosa lagoon is protected under the designation of a Natural Park, so far there are no policies devoted specifically to manage its backbarrier shores. Backbarriers are of local great ecological importance (see Box 2.1), and their management requires integrated coastal studies and management strategies linking not only biodiversity and conservation, but also natural evolution and human usage. Because the exploitation of the Ria Formosa backbarrier and lagoon resources have a relevant contribution to the local economy (see Box 2.2), scientific improvements should look up to the balance between the coastal morphological dynamics and the ecological functions that are hosted by these environments, in an attempt to maintain ecosystem services.

Based on the tendencies highlighted on the previous sections, we propose a simple ecosystem-based management scheme settled in a two-pillar structure, that includes (1) the morphology (type and evolution), and (2) the function (number of functions; e.g. ecological, economic, recreation, amongst others). In Figure 2.12, backbarrier functioning is defined by a flux of sediment (and energy) from the morphology type to the function/service provided. This flux is controlled by internal processes, as small- to long-term behaviours that regulates the morphology type and evolution, and by the environmental characteristics that determines its functioning or provided service (Figure 2.12). External controls account with human interventions that governs the morphological evolutions, and direct uses linked to the provided service. This scheme considers the existence of a dynamic equilibrium crossing the morphology and the function/service, controlled by internal and external processes (Figure 2.12). The scheme illustrates what we consider the most important factors affecting the management of backbarrier shores. It traduces the idea that despite the lower variability of backbarrier shores, and the uncertainty about its future evolution under external environmental changes (as sea-level rise), and equilibrium between backbarrier morphology and related functions is needed to ensure the ecosystem future maintenance.

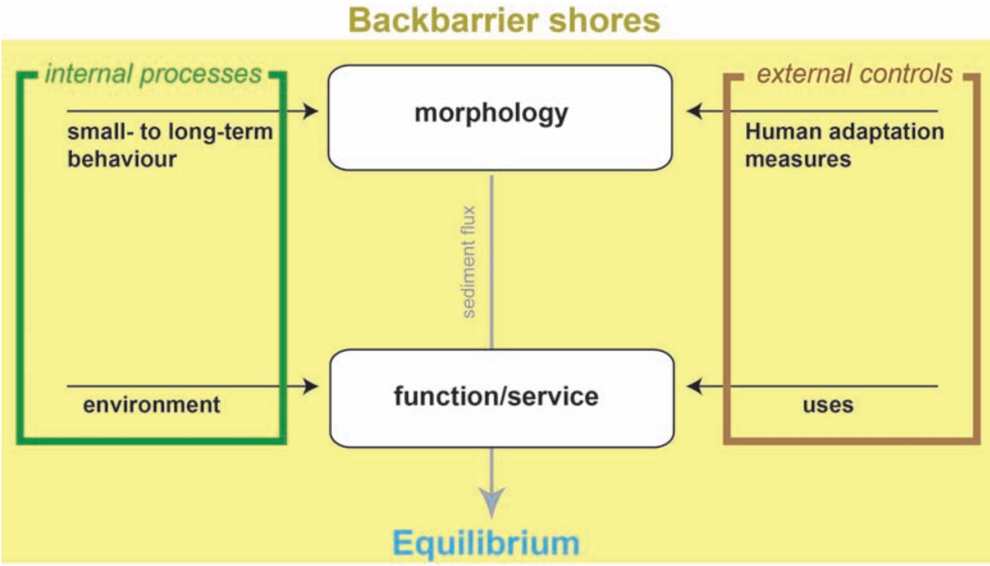


Figure 2.12.
Ecosystem-based scheme for the backbarrier shores along the Ria Formosa lagoon.

Acknowledgements

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References

Andrade, C., Cunha, J. M. & Paulino, J., 1998. Geochemical signature of extreme marine flooding in the Boca do Rio lowland (Algarve, Portugal). *Proceedings of V Congresso Nacional de Geologia*. IGN, SGP, Lisboa, p. C-51/C-54.

Carrasco, A. R., Ferreira, O., Davidson, M. A., Matias, A. & Dias, J. A., 2008. An evolutionary categorisation model for backbarrier environments. *Marine Geology* 251:156-166.

Carrasco, A. R., Ferreira, Ó., Matias, A. & Freire, P., 2012. Natural and human-induced coastal dynamics at a back-barrier beach. *Geomorphology* 159-160:30-36.

Carrasco, A. R., Ferreira, Ó., Matias, A., Pacheco, A. & Freire, P., 2011. Short-term sediment transport at a backbarrier beach. *Journal of Coastal Research* 27:1076-1084.

Carrasco, A. R., Ferreira, Ó. & Roelvink, D., 2016. Coastal lagoons and rising sea level: A review. *Earth-Science Reviews* 154:356-368.

Ciavola, P., Taborda, R., Ferreira, Ó. & Dias, J. A., 1997. Field measurements of longshore sand transport and control processes on a steep meso-tidal beach in Portugal. *Journal of Coastal Research* 13:1119-1129.

Cooper, J.A.G., Pilkey, O. H.& Lewis, D. A., 2007. Islands behind islands: an unappreciated coastal landform category. *Journal of Coastal Research* SI50:907-911.

Dias, J. A., Ferreira, Ó., Matias, A., Vila-Concejo, A. & Sá-Pires, C., 2003. Evaluation of soft protection techniques in barrier islands by monitoring programs: case studies from Ria Formosa (Algarve-Portugal). *Journal of Coastal Research* SI35:117-131.

Ellis, J. Y., Sherman, D. J., Bauer, B. O. & Hart, J., 2002. Assessing the impact of an organic restoration structure on boat wake energy, *Journal of Coastal Research* SI36:256-265.

Garcia, T., Ferreira, Ó., Matias, A. & Dias, J. A., 2002. Recent Evolution of Culatra Island (Algarve – Portugal), In: EUROCOAST (Ed.), *Littoral 2002, The Changing Coast*. EUCC-Porto - Portugal, pp. 289-294.

Kurennoy, D., Parnell, K. E. & Soomere, T., 2011. Fast-ferry generated waves in Southwest Tallinn Bay. *Journal of Coastal Research* SI64:165-169.

Lewis, D. A., Cooper, J. A .G., Pilkey, O. H. & Short, A. D., 2007. Fetch-limited barrier islands of Spencer Gulf, South Australia, *Journal of Coastal Research* SI50:912-916.

Matias, A., Ferreira, Ó., Vila-Concejo, A., Garcia, T. & Dias, J. A., 2008. Classification of washover dynamics in barrier islands. *Geomorphology* 97:655-674.

Nordstrom, K. F., Jackson, N. L., Allen, J. R. & Sherman, D. J., 1996. Wave and current processes and beach changes on a microtidal lagoonal beach at Fire Island, New York, USA In K.F. Nordstrom and C.T. Roman (eds.) *Estuarine Shores*. London: John Wiley & Sons, Ldt. pp. 213-232.

Pacheco, A., Ferreira, Ó., Williams, J. J., Garel, E., Vila-Concejo, A. & Dias, J. A., 2010. Hydrodynamics and equilibrium of a multiple-inlet system. *Marine Geology* 274:32-42.

Pilkey, O. H., Cooper, J. A. G. & Lewis, D. A., 2009. Global distribution and geomorphology of fetch-limited barrier islands. *Journal of Coastal Research* 25:819-837.

Potouroglou, M., Bull, J. C., Krauss, K. W., Kennedy, H. A., Fusi, M., Daffonchio, D., Mangora, M. M., Githaiga, M. N., Diele, K. & Huxham, M., 2017. Measuring the role of seagrasses in regulating sediment surface elevation. *Scientific Reports* 7:11917.

Smith, N. P., 2001. Seasonal-scale transport patterns in a multi-inlet coastal lagoon. *Estuarine Coastal and Shelf Science* 52:15-28.

Vila-Concejo, A., Matias, A., Pacheco, A., Ferreira, Ó. & Dias, J. A., 2006. Quantification of inlet-hazards in barrier island systems. An example from the Ria Formosa (Portugal). *Continental Shelf Research* 26:1045-1060.

Wright, L. & Short, A., 1984. Morphodynamic variability of surf zones and beaches: a synthesis. *Marine Geolgy* 56:93-118.

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

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3.1 What is this Chapter about?

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

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

Box 3.1. Do you know what tides are?

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

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

Box 3.2. Did you know what residence time is?

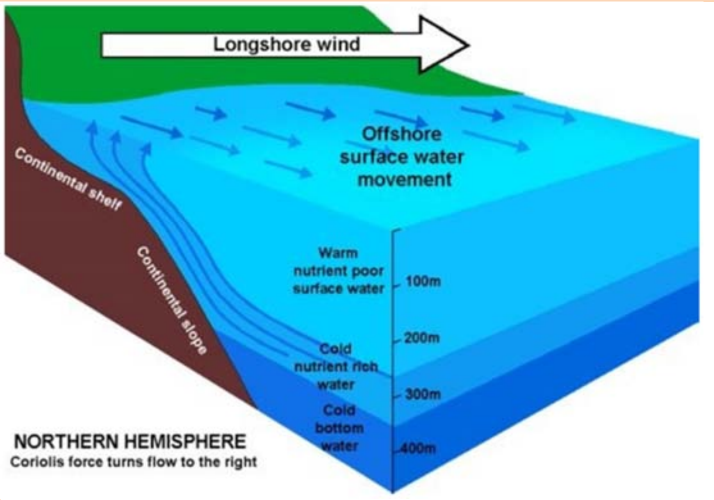
Residence time is the time a particle spends in a reservoir. Residence time is defined as the amount of water in a reservoir divided by either the rate of addition of water to the reservoir or the rate of loss from it. The various reservoirs in the water cycle have different water residence times. The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

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

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

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

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



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

still exists to quantify exchanges, interactions and dynamics between these environments and adjoining ocean. Coupling multidisciplinary data acquired from observations and remote sensing is fundamental to better understand the functioning of these ecosystems.
In the Ria Formosa, the most important coastal lagoon in the south of Portugal, like in other similar systems, the water and

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

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

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

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

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

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

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

3.2. Geographic context and morphology of the Ria Formosa Lagoon

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

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

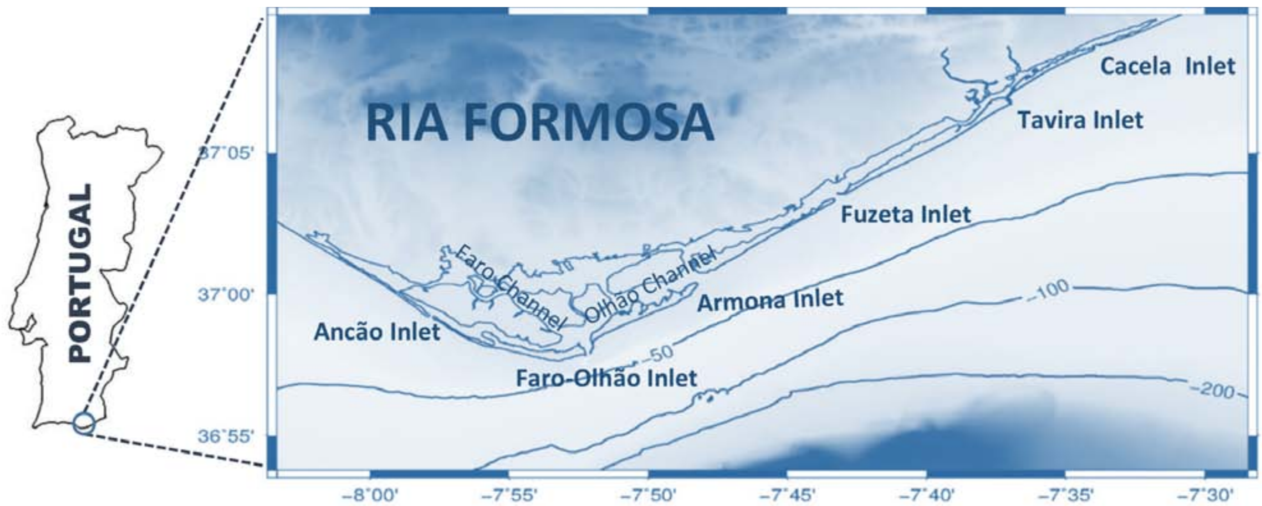


Figure 3.1.
Ria Formosa lagoon location and its western sector with the three main inlets (Ancão, Faro-Olhão and Armona) and the two main channels, Faro and Olhão. Isobathymetric lines of 50, 100 and 200 m deep are also indicated.

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

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

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

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

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

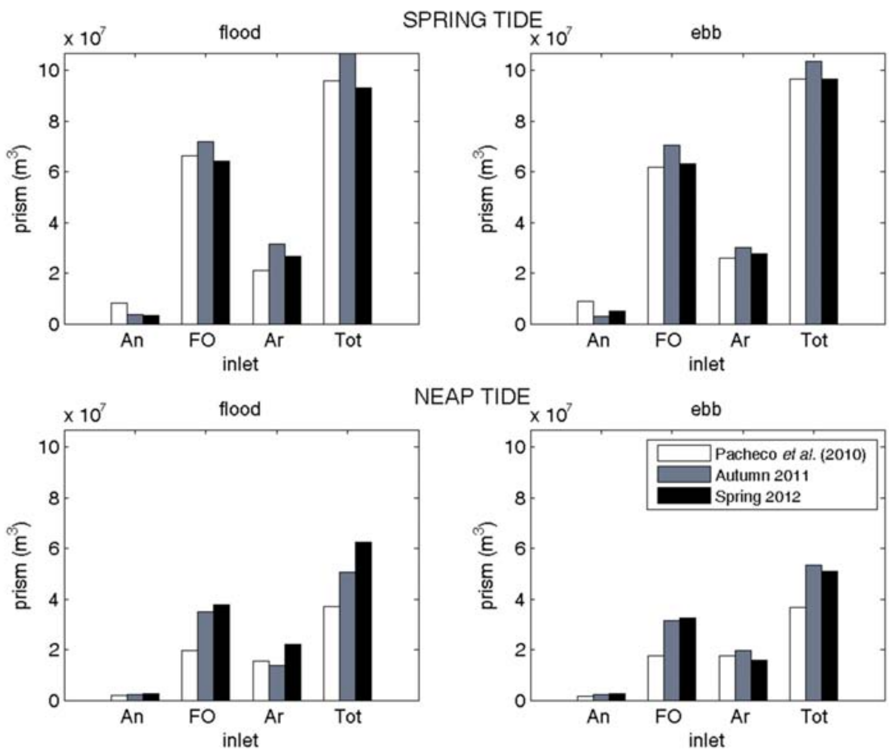


Figure 3.2.
Absolute tidal prisms at the cross sections of the inlets of the western sector of Ria Formosa, An – Ancão inlet, FO – Faro-Olhão inlet and Ar – Armona inlet: results from 2004-2007, considered as reference values from Pacheco et al. (2010) (white bars) in comparison with COALA field experiments,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

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

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

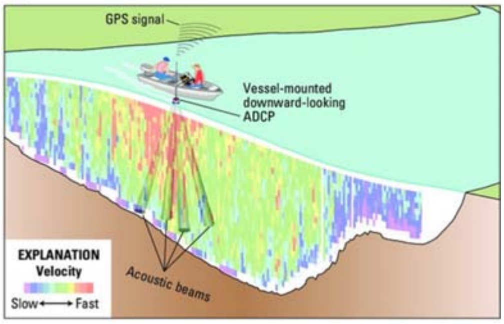
To understand the dynamics of the nutrients and chlorophyll *a* and quantify the exchanges through the main inlets of the western sector several field campaigns along complete tidal cycles were conducted in the last 10 years. The velocity of the currents in the selected sections of the three inlets were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

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

and discharge represents the water volume transport

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

a)



b)

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

Box 3.7. Do you know what measures an ADCP?

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

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

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

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

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

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

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

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

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

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

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

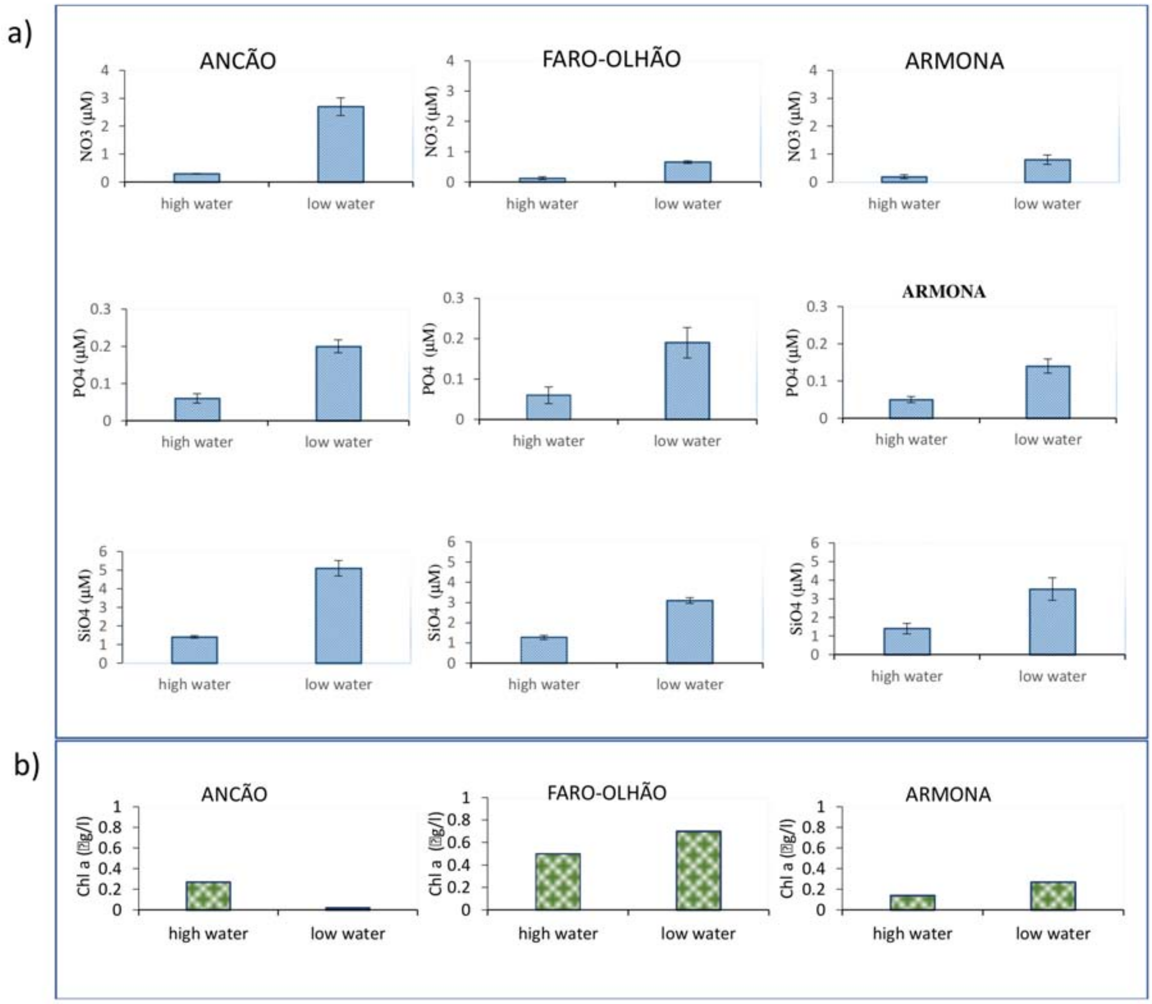


Figure 3.7.
Mean concentration and standard deviation of: a) nitrate-NO3, phosphate-PO4, silicate-SiO4 and b) chlorophyll *a*-Chl a, at high and low water in a spring semidiurnal tidal cycle (22-24 November 2011) at Ancão inlet, Faro-Olhão inlet and Armona inlet.

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

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

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

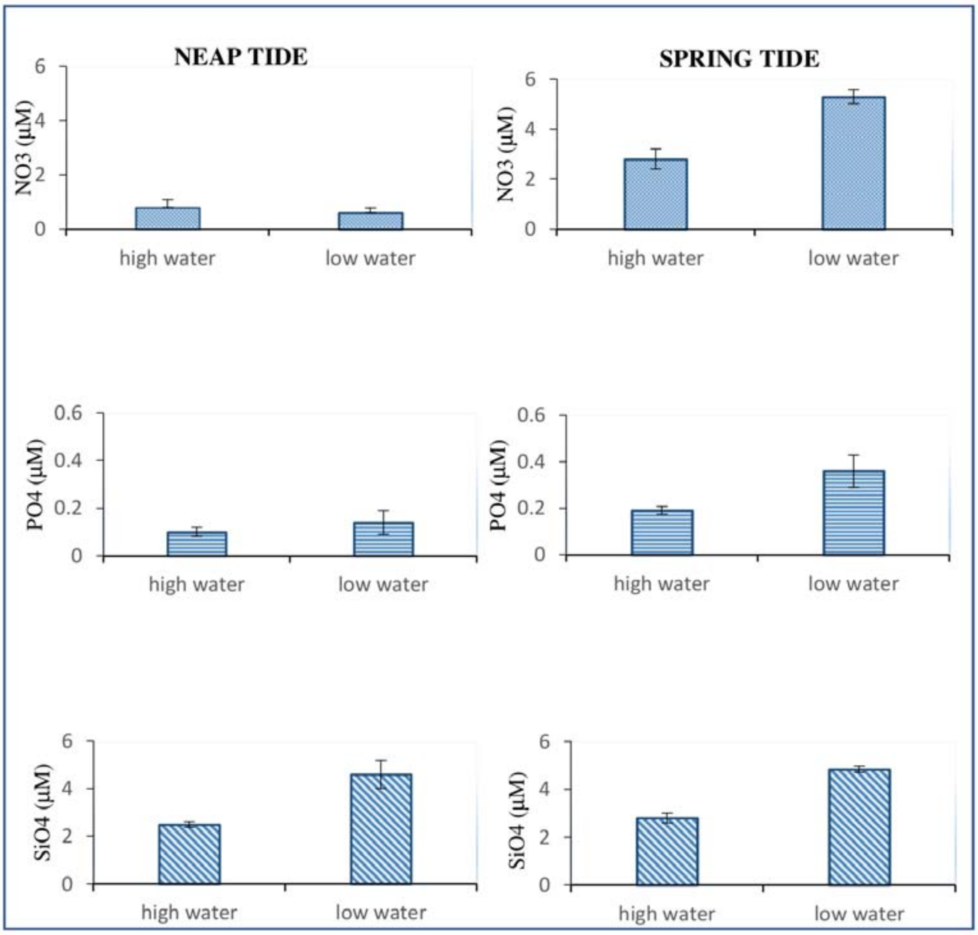


Figure 3.8.
Variability of the mean concentration and standard deviation of nitrate (NO3), phosphate (PO4) and silicate (SiO4) in neap tide (9 October 2012) and spring tide (16 October 2012) at Faro-Olhão inlet during high and low water.

During the spring tidal cycle (Fig. 3.8) the dissolved nutrients presented a notorious contrast between low and high water, pointing to the importance of exchanges between the lagoon and adjoining area, by the calculated tidal prisms at Faro-Olhão inlet (Fig. 3.2), about 9 x10^7 m^3 in spring tide against 6 x10^7 m^3 in neap tide. Nitrate, phosphate and silicate decreased respectively 2 times when the tidal prism was maximum, clearly reflecting their dilution with seawater incoming during the flood of spring tide. Oppositely, in neap tide (Fig. 3.8), when the exchanges were about 30% lower, nitrate and phosphate concentrations were maintained low and similar at both low and high water, while silicates decreased 2 times at high water and reached maximum mean concentrations (4.6 mM) at low water also reflecting the dilution effect. This difference points to the sharp silicate regeneration in sediments and diffused out to water column as shown in other studies conducted in Ria Formosa (Falcão and Vale, 2003; Duarte et al., 2008).
Comparing the mean concentrations of nitrate at neap and spring tide (Fig. 3.8) we found values about four times higher when the lagoon was under maximum oceanic influence (spring tide). This fact may be attributed to the occurrence of a coastal upwelling event during this tidal cycle, that transported an overload of nutrients to the lagoon. In fact, during the spring tidal cycle, at the beginning of the flood phase, nitrate concentrations increased reinforcing that coastal water was enriched in nitrate, as reported in other studies in the Ria Formosa inlets (Falcão and Vale, 2003; Newton et al., 2005), probably due to the nitrification process prevailing there.

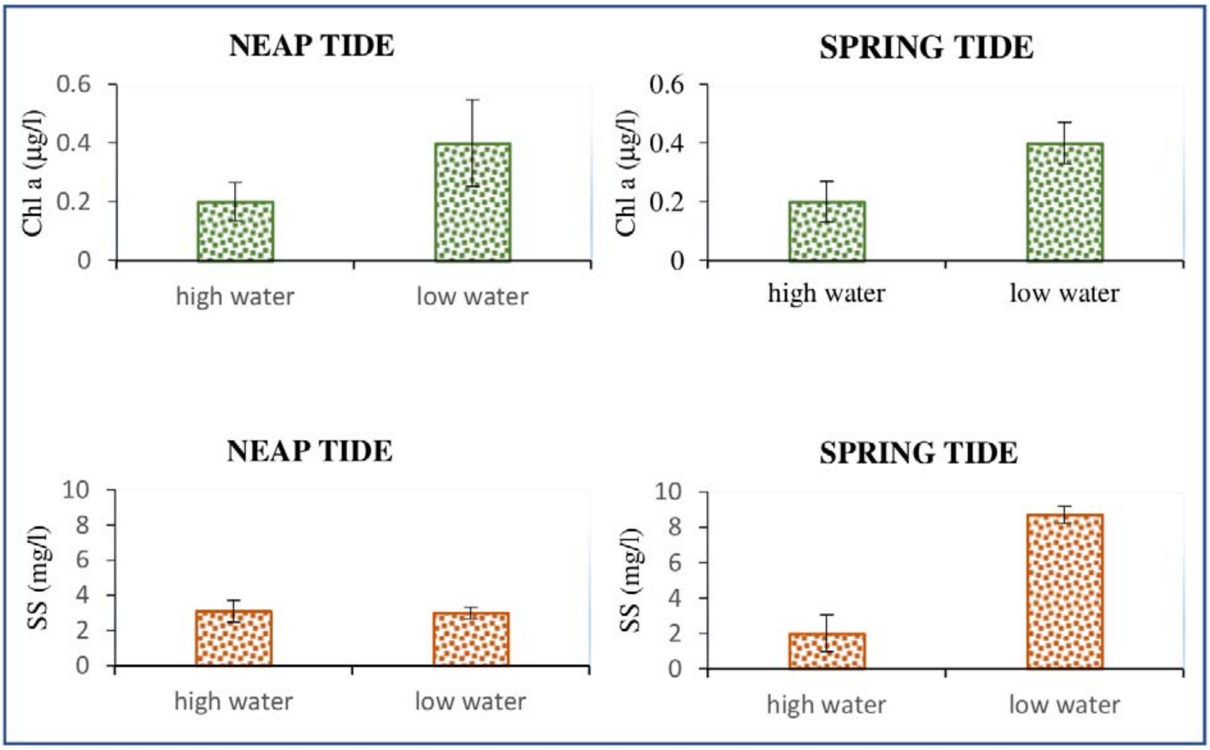


Figure 3.9.
Variability of the mean concentration and standard deviation of chlorophyll a (Chl a) and suspended solids (SS) in neap tide (9 October 2012) and spring tide (16 October 2012) at Faro-Olhão inlet during high and low water.

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

higher than obtained at high water, which may be due to resuspension effect felt during the ebb period, when the currents through the inner lagoon channels may be important. Moreover, this fact suggests that its major source is inside the lagoon and that by dilution effect the concentrations decreased during the flood period, with the incoming coastal water, usually poorer in particulate material.
The pattern of variability of the water characteristics can change temporally, dependent on the hydrodynamics and circulation between this inlet, the channels and the other inlets, internal processes including biological activity or even due to variability of other driving forces associated to environmental conditions like meteorological and oceanographic processes occurring in the adjacent ocean that will affect the inner areas of the Ria Formosa.
In fact, the tidal variability is not the only driving mechanism responsible for the differences between field surveys. There are also other forcing mechanisms to consider namely meteorological/oceanographic drivers. Winds are quite relevant for this issue. Under westerlies, upwelling is a recurrent process that occurs in the south coast of Portugal, more frequently between April and October (Relvas & Barton, 2002). For example, in Autumn of 2012, between the consecutive spring and neap tidal cycles (Figs. 3.8 and 3.9) an upwelling event occurred as reflected in a decrease of sea surface temperature recorded by a sensor coupled to a Pressure Transducer (PT) deployed in a pier at the Deserta Island (Fig. 3.10). This provides information to better understand the processes involved in the Faro-Olhão Inlet.
As can be seen in Fig. 3.10, under a period of prevailing west winds there was an evident decrease of the water temperature (*ca.* 5 °C) accompanied by a decrease of the sea level. Those characteristics are typical of coastal upwelling events. However, it was also observed that after the last campaign the wind relaxed. These conditions will have an insightful signature in the budgets of mass exchanges through the Faro-Olhão inlet, as further described in the following section.

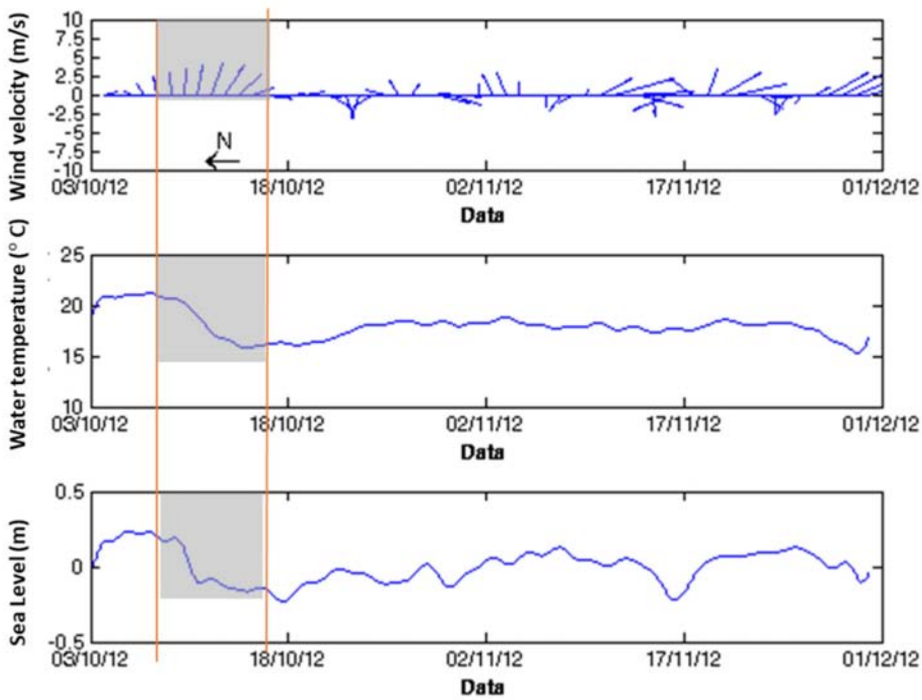


Figure 3.10.
Data acquired by the PT deployed at the Deserta Island pier, in the period between 3 October and 1 December 2012: velocity and direction of the wind from the Faro Airport weather station; water temperature and sea level. N indicates the north direction. The period in between the two surveys is indicated by the grey box, delimited by the two orange lines.

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

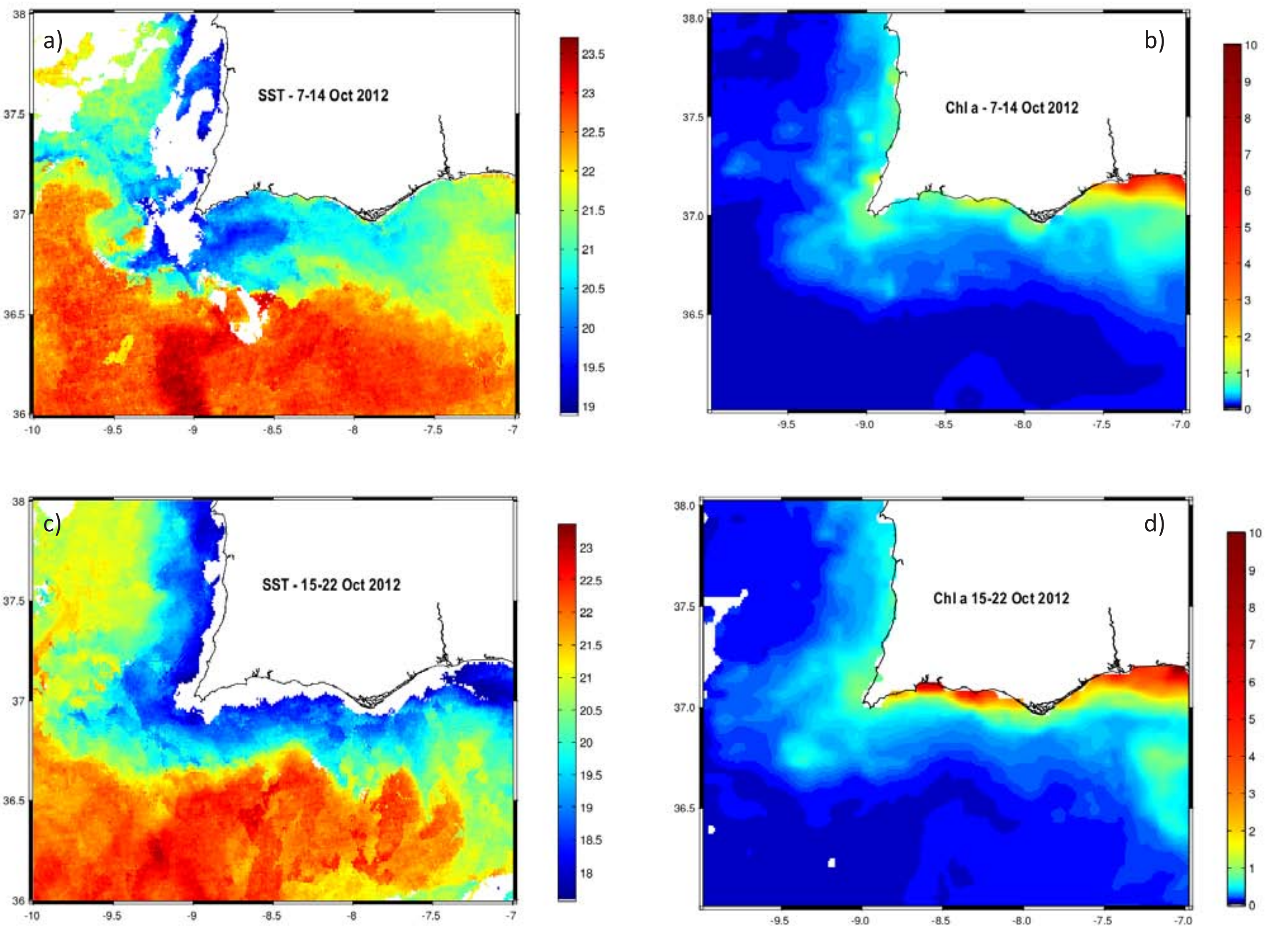


Figure 3.11.
Weekly composite SST and chlorophyll *a* satellite images in the south coast of Portugal, covering the period of the neap (9 October) and spring tide (16 October) for the Autumn 2012 campaigns: a) SST and b) Chlorophyll *a* for 7-14 October, c) SST and d) Chlorophyll *a* for 15-22 October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

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

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

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

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

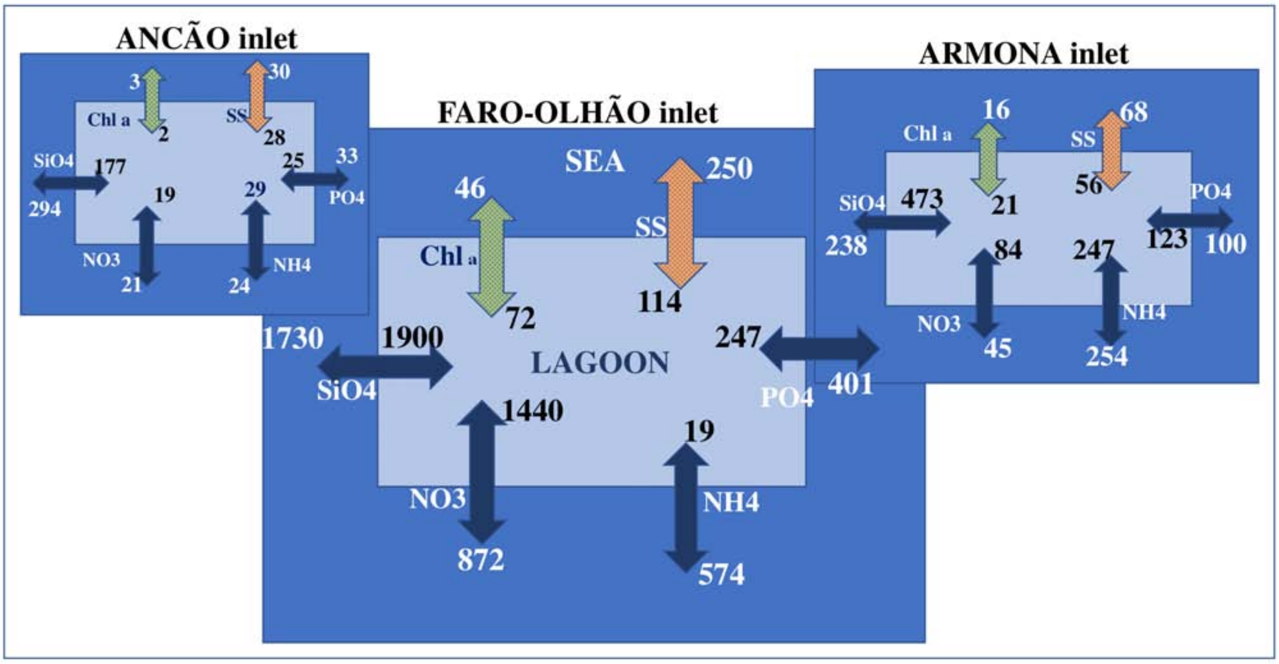


Figure 3.12.
Conceptual representation with arrows for inflows and outflows relative to Chlorophyll *a* (kg) - green, suspended solids (ton) - orange and nutrients (kg) – dark blue, between the three inlets of the western sector of Ria Formosa (lagoon – light blue) and the coastal ocean zone (sea – intermediate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

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

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

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

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

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

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

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

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References

Allen, G., Mandelli, E. & Zimmermann, J. P. F., 1981. Physics, geology, chemistry, p.29-50 *in* Lasserre, P. and Postma, H. Eds. *Coastal lagoon research, present and future: proceedings of a seminar.* UNESCO Technical Papers in Marine Science 32. United Nations Educational, Scientific, and Cultural Organization, Paris, France.

Barbosa, A.B., 2010. Seasonal and inter-annual variability of planktonic microbes in a mesotidal coastal lagoon (Ria Formosa, SE Portugal): impact of climatic changes and local-human influences, in: H. Paerl, M. Kennish, Eds., *Coastal Lagoons: critical habitats of environmental change*, CRC Press, Taylor & Francis Group, Marine Science Book Series, Boca Raton, pp. 335-366.

Bird, E. C. F., 1994. Chapter 2. Physical setting and geomorphology of coastal lagoons. P. 9-40 *in* Kjerfve, B., Ed. *Coastal lagoon processes.* Elsevier, Amsterdam, The Netherlands.

Cravo, A., Cardeira, S., Pereira, C., Rosa, M., Madureira, M., Rita, F., Luís, J. & Jacob, J., 2013. Nutrients and particulate matter exchanges through the Ria Formosa coastal lagoon. *Journal of Coastal Research* SI 65: 1999-2004.

Cravo, A., Cardeira, S., Pereira, C., Rosa, M., Alcântara, P., Madureira, M., Rita, F., Luis, J. & Jacob, J., 2014. Exchanges of nutrients and chlorophyll *a* through two inlets of Ria Formosa, South of Portugal, during coastal upwelling events. *Journal of Sea Research* 93: 63-74.

Duarte, P., Azevedo, B., Guerreiro, M., Ribeiro, Bandeira, R., Pereira, A., Falcão, M., Serpa, D., & Reia, J., 2008. Biogeochemical modelling of Ria Formosa (South Portugal). *Hydrobiologia* 611: 115-132.

Fabião, J., Rodrigues, M., Fortunato, A. B., Jacob, J. & Cravo, A., 2016. Water exchanges between a multi-inlet lagoon and the ocean: the role of forcing mechanisms. *Ocean Dynamics* 66 (2): 173-194.

Falcão, M. & Vale, C., 1998. Sediment-water exchanges of ammonium and phosphate in intertidal and subtidal areas of a mesotidal coastal lagoon (Ria Formosa). *Hydrobiologia* 373/374: 193-201.

Falcão M. & Vale C., 2003. Nutrient Dynamics in a Coastal Lagoon (Ria Formosa, Portugal): The importance of lagoon-sea water exchanges on the biologic productivity. *Ciencias Marinas* 29(3): 425-433.

Ferreira, O., Matias, A. & Pacheco, A., 2016. The east coast of Algarve: a barrier island dominated coast. *Thalassas: An International Journal of Marine Sciences* 32(2): 75–85.

Jacob, J., Cardeira, S., Rodrigues, M., Bruneau, N., Azevedo, A., Fortunato, A.B., Rosa, M. & Cravo, A., 2013. Experimental and numerical study of the hydrodynamics of the western sector of Ria Formosa. *Journal of Coastal Research* 65: 2011-2016.

Jacob, J. & Cravo, A., 2016. Evolution of the tidal prisms at the inlets of the western sector of Ria Formosa before the relocation of the Ancão inlet in November 2015. In Instituto Hidrográfico. Actas das 4as Jornadas de Engenharia Hidrográfica, 21-23 de Junho de 2016, Lisboa, pp.207-210.

Kjerfve, B., Ed., 1994. *Coastal lagoon processes.* Elsevier, Amsterdam, The Netherlands.

Mueller, D. S., Wagner, C. R., Rehmel, M. S., Oberg, K. A. & Rainville, F., 2013. Measuring Discharge with Acoustic Doppler Current Profilers from a Moving Boat. Chapter 22 of Section A, Surface-Water Techniques. Book 3, Applications of Hydraulics. U.S. Geological Survey, Reston, Virginia, 95 p.

Newton A. & Mudge, S., 2005. Lagoon-sea exchanges, nutrient dynamics and water quality management of the Ria Formosa (Portugal). *Estuarine, Coastal and Shelf Science* 62, 405-414.

Nixon, S. W., 1995. Coastal marine eutrophication: a definition, social causes, and future concerns. *Ophelia* 41, 199-219.

Pacheco, A., Ferreira. Ó., Williams, J.J., Garel, E., Vila-Concejo, A. & Dias, J. A., 2010. Hydrodynamics and equilibrium of a multiple-inlet system. *Marine Geology* 274: 32–42.

Pacheco, A., Ferreira, Ó. & Williams, J. J., 2011. Long-term morphological impacts of the opening of a new inlet on a multiple inlet system. *Earth Surf Processes and Landforms*, 36, 1726–1735.

Pilkey, O., Neal, W., Monteiro, J. H. & Dias, J. A., 1989. Algarve barrier islands: a noncoastal-plain system in Portugal. *Journal of Coastal Research*, 5(2), 239–261.

Popesso, C., Pacheco, A., Ferreira, O. & Fontolan, G., 2016. Evolution of a relocated inlet migrating naturally along an open coast. *Journal of Coastal Research*, SI 75, 233-237.

Relvas, P. & Barton, E. D., 2002. Mesoescale patterns in the Cape São Vicente (Iberian Peninsula) upwelling region. *Journal of Geophysical Research* 107 (C10), 3164: 28 (1-23).

Vila-Concejo, A., Ferreira, O., Matias, A. & Dias, J. M. A., 2003. The first two years of an inlet: Sedimentary dynamics. *Continental Shelf Research* 23, 1425-1445.

4. The role of Ria Formosa as a waste water receiver

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Ria Formosa is a system of barrier islands that communicates with the sea through six inlets, situated in the Algarve, the most southern region of Portugal which encompasses the municipalities of Loulé, Faro, Olhão, Tavira and Vila Real de Santo António, covering an area of about 18,400 hectares along a 60 km stretch from the Ancão beach to Manta Rota beach (Figure 4.1). It is an area protected by the status of Natural Park, granted by Law n.º 373/87 of December 9th and its classified as a sensible area according to the law n.º 152/97 of June 19th concerning urban waste water discharges, in order to assure water quality standards for shellfish aquaculture. This ecosystem is very important from the socio-economic point of view, being responsible for 41% of the Portuguese national production of bivalve shellfish, with a small finfish production (IMAR, 2012).

Figure 4.1.
Algarve's Sanitation Multi-Municipal System.

The Ria Formosa is the receiving environment of six Waste Water Treatment Plants (WWTP) (see Box 4.1)

Box 4.1. What are Waste Water Treatment Plants?

WWTP are infrastructures composed by a set of processes, with the main objective to remove the contaminant loads in the waste water. There are different types of biological treatment, the treatment process chosen must be fitted to the required quality of treated waste water disposed in the receiving environment. Also, the size and design of the WWTP depends on the waste water flowrate and contaminant loads. (Davis, 2010). A typical municipal WWTP may include primary treatment to remove solid material, secondary treatment to digest dissolved and suspended organic material as well as the nutrients nitrogen and phosphorus, and – sometimes but not always – disinfection to kill pathogenic bacteria. The sewage sludge that is produced in sewage treatment plants undergoes sludge treatment.

in the region: Quinta do Lago, Faro Noroeste, Faro Nascente, Olhão Poente, Olhão Nascente and Almargem (Figure 4.1). These WWTP are managed by Águas do Algarve that is the concessionaire of the Algarve's Sanitation Multi-Municipal System, managing the infrastructures for interception, treatment and final disposal of waste water collected from the Algarve's sixteen Municipalities. The system has 447.3 kilometres of drainage systems, 175 waste water pumping stations and 66 WWTP.

This chapter details the impact of the faecal coliform plumes from the discharges of treated waste water from three WWTP (Almargem, Faro Noroeste and Faro/Olhão) by the use of mathematical modelling for the simulation of hydrodynamic variables, water quality and bacteriological tracers.

Box 4.2. What is Mathematical modelling?

Modeling is an experimental tool for testing theories and assessing quantitive conjectures. A mathematical model usually describes a system by a set of variables and a set of equations that establish relationships between the variables. The variables represent some properties of the system, for example, measured system outputs often in the form of signals, timing data, counters, etc. Mathematical modeling has many applications in sciences and can be used to simulate tide, weather, Planning of production units, wind channel simulations, car crash simulations, etc.

4.1. Modelling the dispersion of waste water

The mathematical modelling (see Box 4.2) of waste water plumes is a tool that enables the prediction of water quality, enables the adjusting of the discharge point of new WWTP and supports decision making in case of discharges due to malfunctions in the WWTP. The MOHID Water Modelling System (MARETEC, 2018) was used as an integrated modelling tool, capable of simulating physical and biogeochemical processes in coastal systems. MOHID Water is responsible for the modelling of hydrodynamic processes, simulation of dispersion phenomena (lagrangian and eulerian methodologies, see Box 4.3), wave propagation, sediment transport, water quality / biogeochemical processes in the water column and exchanges with the bottom (Neves et al., 2000). The model allows to simulate the main physical mechanisms such as density gradients (baroclinic flows), tide, wind and fresh water inflows (Martins et al., 2001).

The main forces in the Ria Formosa are tidal and freshwater flow. Forcing due to wind is negligible since the fetch distance in this system is small. Calibration and validation of the hydrodynamic component was

Box 4.3. What is the difference between Eulerian and Lagrangian aproach?

Essentially all the relevant models for the simulation of coastal and ocean processes deal with the same basic principle of transport by advection and diffusion of a property in a moving medium (water). There are two different approaches to describe that process: the Lagrangian approach and the Eulerian approach. In the Lagrangian approach the focus is on a specified volume of water, called the system, and its evolution is followed through space and time. In the Eulerian approach the focus is on a specified portion of space, the control volume, and the evolution of the properties associated to the water inside the control volume is monitored while fluxes of water are allowed to flow in and out from it (Zhao et al., 2011).

performed by comparing the results of the model, in the form of time series, with measurements made during continuous field campaigns.
The calculation of water quality properties evolution is done using a specific module: the Water Quality module. This module is responsible for calculating the terms related to the sources and sinks, specific for each fundamental property, in each of the cells of the mesh and at each instant (Martins et al., 2003).
Simulation of the WWTP plumes was done using a Lagrangian type transport model. In this model the discharge water mass is associated with individual water masses that are released at short intervals from a fixed location in space and are carried by the model. These masses of water (particles) thus undergo advective transport by the field of velocities and diffusive transport due to the volume variation of the particle. Additionally, a random variation in the trajectory is included to account for large size turbulence (Allen, 1982). The microbiological properties of the discharge varies due to both dilution and mortality. The mortality law for faecal coliforms used considers the effects of radiation, temperature, and salinity.

4.2. Almargem WWTP

The Almargem WWTP is located on the left bank of the Almargem stream in Tavira. The treated effluent is discharged into the Almargem water stream, in the vicinity of Ria Formosa. This installation was designed to serve an equivalent population of 48,200 equivalent inhabitants during summer time, 12,200 m^3/day in the year of 2025. The treatment system implemented is of secondary level by activated sludge, and UV disinfection. The Almargem WWTP began its service in May 2007 and due to its construction the served area was increased, leading to the decommissioning of the Tavira and 5 other smaller low technology WWTP. The discharge limits for the treated effluent issued by the Environmental Portuguese Agency (APA) are 25 mg/L O_2 of BOD, 125 mg/L O_2 of COD, 35 mg/L of TSS and 2000 CFU/100mL of faecal coliforms (see Box 4.4).

Box 4.4. Did you know that…

Coliform bacteria generally originate in the intestines of warm-blooded animals. Faecal coliforms are capable of growth in the presence of bile salts or similar surface agents, are oxidase negative, and produce acid and gas from lactose. Large quantities of fecal coliform bacteria in water indicate a higher risk of pathogens being present in the water. Some waterborne pathogenic diseases that may coincide with fecal coliform contamination include ear infections, dysentery, typhoid fever, viral and bacterial gastroenteritis, and hepatitis A. Untreated organic matter that contains fecal coliform can be harmful to the environment. Aerobic decomposition of this material can reduce dissolved oxygen levels if discharged into rivers or waterways. This may reduce the oxygen level enough to kill fish and other aquatic life.
Most Probable Number (MPN) a method used to estimate the concentration of viable microorganisms in a sample by means of replicate liquid broth growth in ten-fold dilutions. It is commonly used in estimating microbial populations in soils, waters, agricultural products.

4.2.1. System hydrodynamics

Ria Formosa hydrodynamics can be subdivided into two independent regions: The Western Region, spanning from the beginning of the Ancão Peninsula to the Marim Channel and the Eastern Region that stretches from the Marim channel to the end of the Cacela Peninsula, covering the Almargem riverbank. The Eastern region is characterized by less extensive wetland zones and a single main channel, responsible for transport, in the direction parallel to the barrier islands. From the hydrodynamic point of view this means that the residence time is inferior to the one of the Western region. The hydrodynamics of the two regions are virtually independent since they are only connected by the *Marim* channel which has a reduced transport capacity.
Velocities are higher in the Spring Tide in the periods of flood and ebb tide, with maximum velocities of the order of 0.5m/s while in Neap Tide in the periods of flood and ebb tide the maximum velocities are of the order of 0.3 m/s. The maximum speeds occur mainly in the deepest channels such as the Barra de Tavira and the Cabanas Channel. The velocities in the Gilão River are smaller during the ebb tide than in the flood tide in both Spring and Neap tide (Figure 4.2).

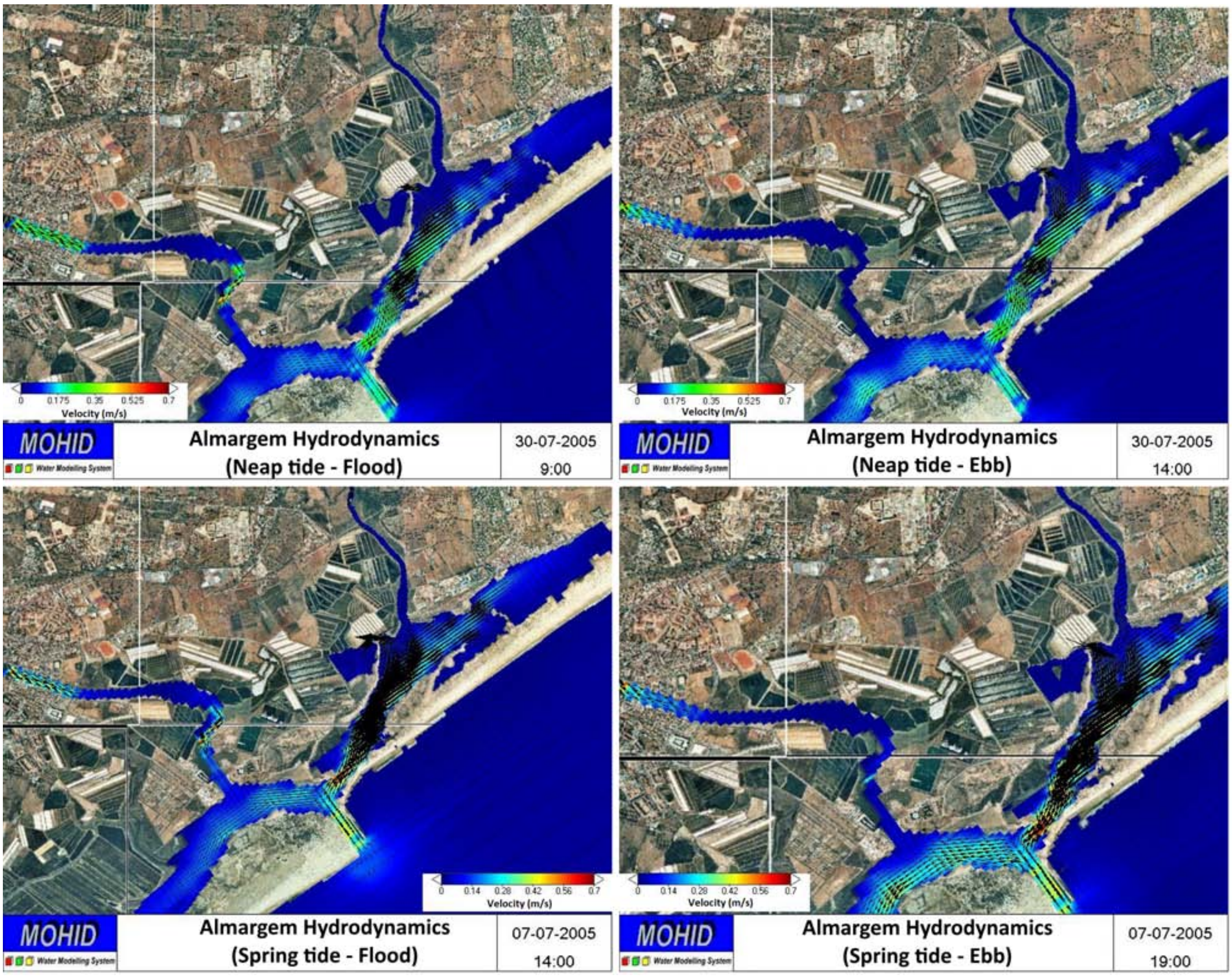

Figure 4.2.
Hydrodynamics model results for Spring and Neap tide in the Almargem system

The Almargem water stream presents low velocities in the flood and ebb tide in both Spring and Neap Tide.

4.2.2. Waste water plumes

The simulation of faecal coliform plumes associated with the discharge of the Tavira WWTP were performed by forcing the Lagrangian transport model with the previously calibrated velocity fields. For this a continuous discharge was considered with a 10,000 MPN/100 ml concentration of faecal coliforms and a variable T_{90} in time as a function of temperature, solar radiation and salinity. Figure 4.3 shows the results obtained for the simulation of the discharge plume of the Tavira WWTP. The same figure also shows the discharge of Almargem WWTP, with a discharge of 2000 MPN/100 ml, used in the study of different scenarios before the construction.

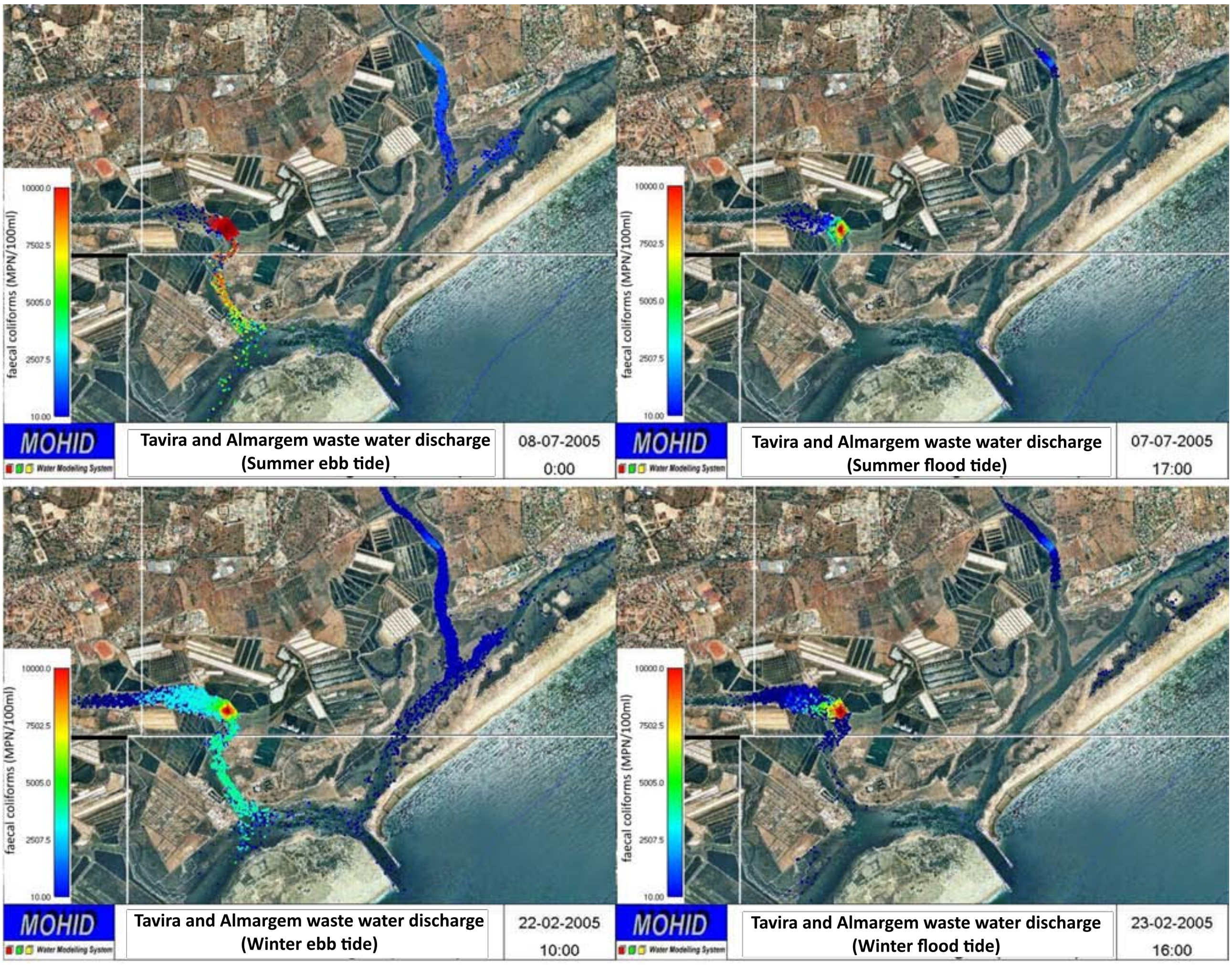

Figure 4.3.
Waste water plume dispersion associated to the discharges of Tavira and Almargem WWTP for different season and tide conditions.

The concentrations in the plume along the estuary depend mainly on the tide situation and the season and time of day due to the solar radiation factor. In an ebb tide situation, the transport of the plumes are carried out downstream of the discharge, following the deeper channel, where the dispersion produces lower concentrations due to the dilution effect. In flood tide conditions, the plumes are transported upstream of the discharge. Concentrations of faecal coliforms in winter are higher than in summer due to lower solar radiation, inducing a decrease in faecal coliform mortality.
For the Almargem WWTP, three different scenarios of a continuous discharge with a concentration of 2,000 NMP/100 ml of faecal coliforms were simulated and a T_{90} to be varied in time as a function of

temperature, solar radiation and salinity at different locations in the domain in study. In scenario I the discharge is carried out in the middle of the Almargem channel, in scenario II the discharge is carried out in the downstream region of the Almargem channel and in scenario III the discharge is carried out in the Cabanas channel. The objective was to simulate various locations for the actual discharge of the Almargem WWTP, to try to minimize its negative effects on the surrounding environment. Figure 4.4 show the expected results for each scenario in one of the various tide situations considered.

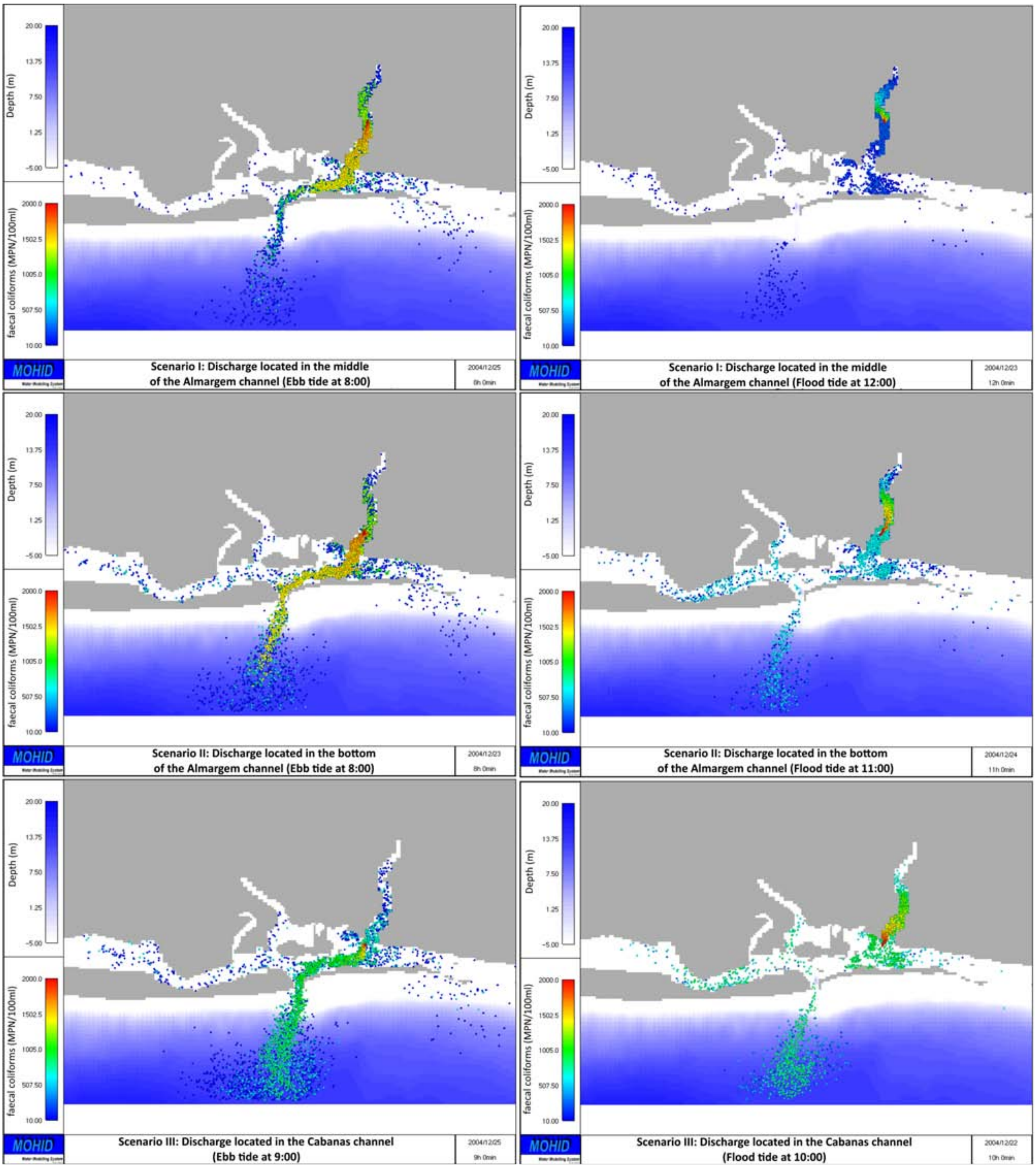

Figure 4.4.
Expected results for three different discharge locations of the Almargem WWTP.

In the region associated to the Almargem, Rio Gilão and Cabanas channels, the microbiological campaigns showed that the situation in the Gilão River is significantly different from that found in the rest of the domain. Microbiological concentrations in the Gilão River are close to or even above the limit value for bathing waters. For the remaining domain the values are always below the limit value. These results show that the discharges of the Tavira WWTP cause some impact on the Gilão River, but that dilution and inactivation are sufficient to prevent this impact from reaching the bathing areas. On the other side, it also shows that the situation in the Almargem channel, even without any point discharge in its interior, already presents concentrations similar to those of the Cabanas channel. This may be due to upstream discharges from the stream. The mathematical modelling results confirmed these observations, the concentrations of the plumes discharged by Tavira WWTP are higher in the interior of the Gilão River, having a strong dispersion in the region between the *quatro Águas* dock and the *Barra de Tavira*. The concentrations that spread to the beaches outside the sandbanks are therefore low. In the model results the effects of solar radiation on inactivation can be observed, producing plumes with higher microbiological concentration at night. Even in this case the impact on bathing waters is reduced. In the three different scenarios simulated it was verified that the upstream discharges produce a greater contamination within the Almargem channel but the concentrations in the Cabanas channel and especially in the outer coastal region are low. With the discharges located in the Cabanas Channel the concentration in the Almargem River is substantially lower, but the concentrations in the interior of the Ria Formosa extend to a much higher area and there is also some impact on the outer coastal region.

4.3. Faro Noroeste WWTP

The Intermunicipal WWTP of Faro Noroeste went into operation in August 2009, and the old lagoon system was abandoned. The new WWTP was built based on the treatment needs of the project horizon, which represents a 400% increase over the nominal capacity of the old plant and the new quality objectives defined for the final effluent of the WWTP. The new WWTP has a treatment capacity of 44,530 habitants, in summer season, 13,221 m^3/day in the year of 2033.

Figure 4.5.
Faro Noroeste WWTP. 1 - Preliminary treatment/Sludge dewatering building; 2 - Biological reactors (Oxidation ditch) 1 & 2; 3 - Secondary clarifiers 1 & 2; 4: UV Desinfection. Credits: Águas do Algarve, S.A.

The treatment scheme is developed along two lines, based on a biological treatment system by activated sludge, in a prolonged aeration regime, in two biological reactors with the oxidation ditch configuration and with surface aerators. The final effluent of the Faro Noroeste WWTP is the *Esteiro do Ramalhete*, in Ria

Formosa. The discharge limits for the treated effluent issued by APA are 25 mg/L O_2 of BOD, 125 mg/L O_2 of COD, 35 mg/L of TSS and 300 CFU/100mL of faecal coliforms.

4.3.1. System hydrodynamics

The region of Faro Noroeste is included in the Western Region of Ria Formosa, which stretches from the beginning of the Ancão Peninsula to the Marim Channel. This region is shallow, and hydrodynamics essentially depends on the tide. The tidal prism in this zone (difference between the volume of water in high tide and in the low tide) is higher than the volume of water in low tide. For this reason, the average residence time is small, of the order of one day (Neves et al, 1996; Dias et al, 2009). This explains the good dispersion capacity of this region.

In this system the highest speeds are found in the Ria Formosa bars and Faro main channel. In these places the transport is more efficient, giving short residence times. Globally there is also a generalized velocity difference between Spring and Neap tide conditions, with the flow pattern being the same (Figure 4.6).

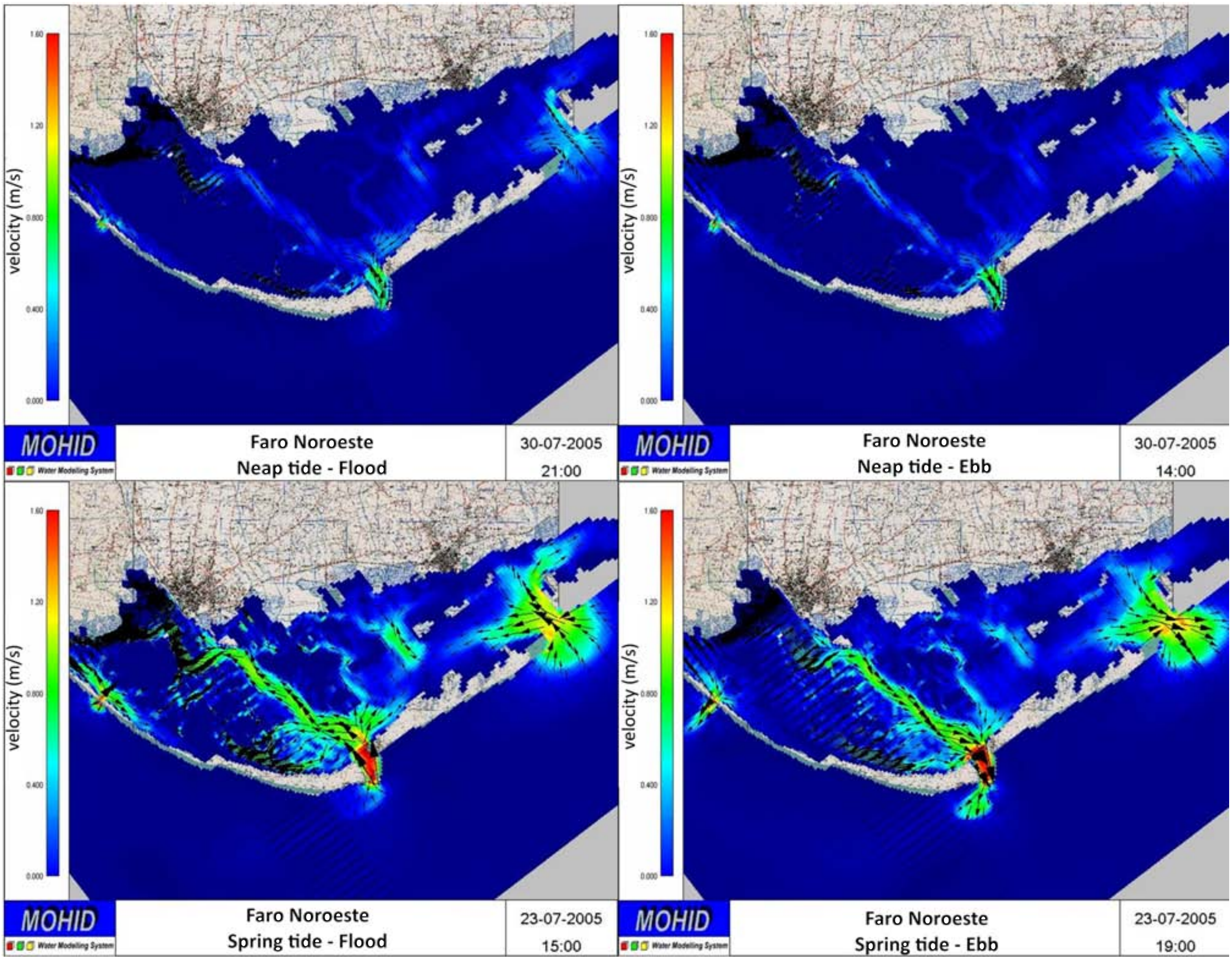

Figure 4.6.
Hydrodynamics model results for Spring and Neap tide in the Faro Noroeste system.

The transient velocity fields show that the highest velocities occur in the Ria Formosa opening, whereas the smaller ones occur in the confined zones of the lagoon. For example, in the Faro bar the speed is higher than 1 m/s, while in the Ramalhete channel the maximum speed is of the order of 0.5 m/s.

4.3.2. Waste water plumes

The simulation of coliform plumes at the Faro Noroeste WWTP was performed for a discharge of 1×10^4 MPN/100 ml of faecal coliforms, which corresponds to average value discharged for the old WWTP. This value corresponds to the limit value imposed by the discharge license. The value was changed to 300 MPN/100 ml in order to meet the minimum quality objectives of shellfish waters.

The dispersion of the faecal coliform plumes for the winter season and different tide conditions is represented in Figure 4.7.

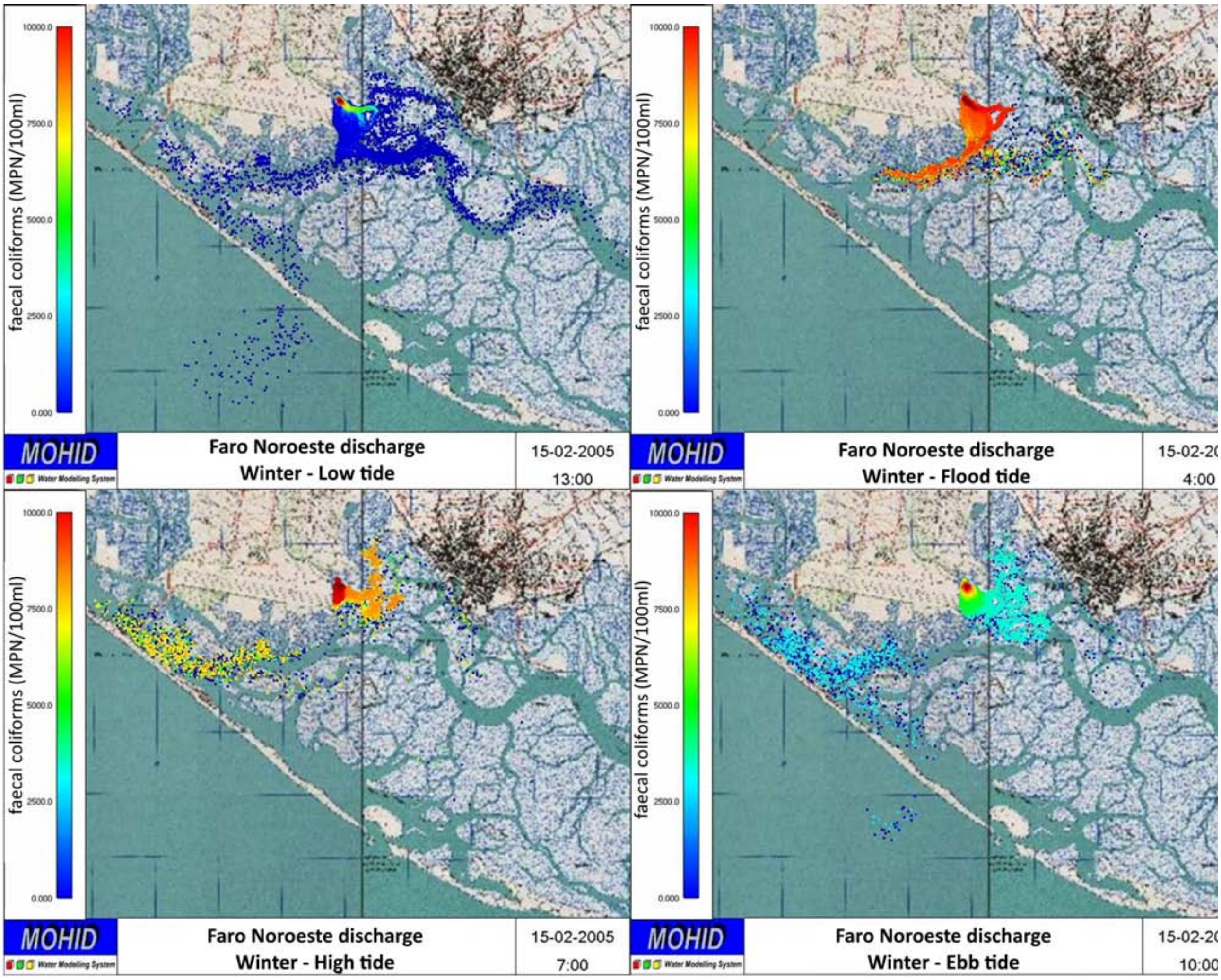

Figure 4.7.

Waste water plume dispersion associated to the discharge of Faro Noroeste WWTP for winter season and different tide conditions.

The dispersion of the faecal coliform plumes for the summer season and different tide conditions, is represented in Figure 4.8.

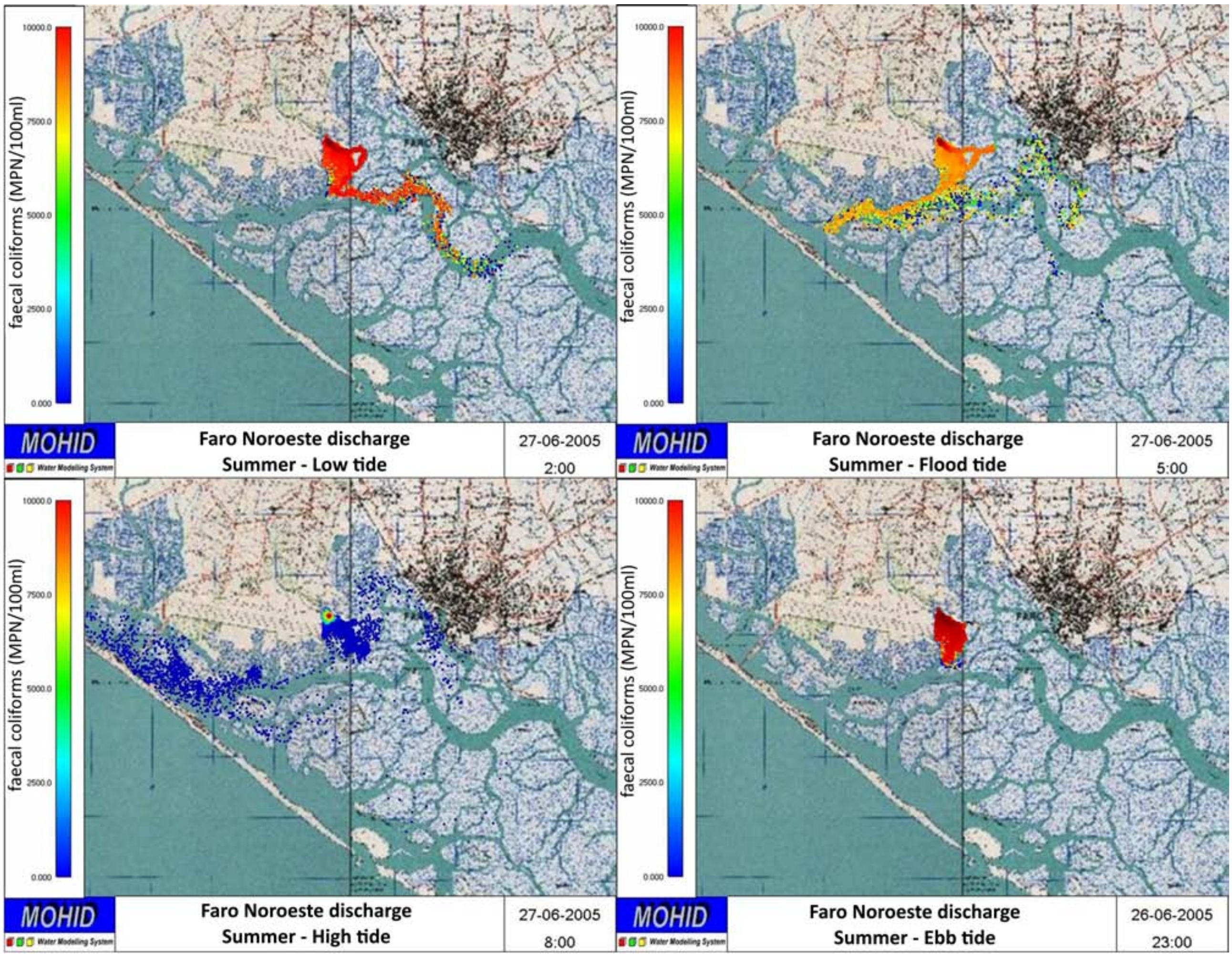

Figure 4.8.
Waste water plume dispersion associated to the discharge of Faro Noroeste WWTP for summer season and different tide conditions.

The faecal coliform plumes are transported during the ebb tide along the Ramalhete channel and the Faro main channel towards the Faro-Olhão bar. During the day the concentration of the faecal coliforms plume in the water column is only significant for a relatively small area. At night, the plume length is larger and more concentrated, extending to a significant part of the Faro channel. This situation is explained by less inactivation during this period.
During flood and high tide the plumes are transported towards the Ancão bar and to the region of Montenegro to the North. Comparing the winter situation with the summer it is worth noting the decrease in the faecal coliform plume in the summer, due to the greater inactivation of these by an increase in solar radiation.
For this WWTP, only one discharge scenario was performed, with a coliform concentration in the order of 1×10^4 MPN/100 ml, 400 m downstream of the current discharge. For this scenario two transport situations of the faecal coliform plumes are presented, one for flood tide and another for ebb tide Figure 4.9.

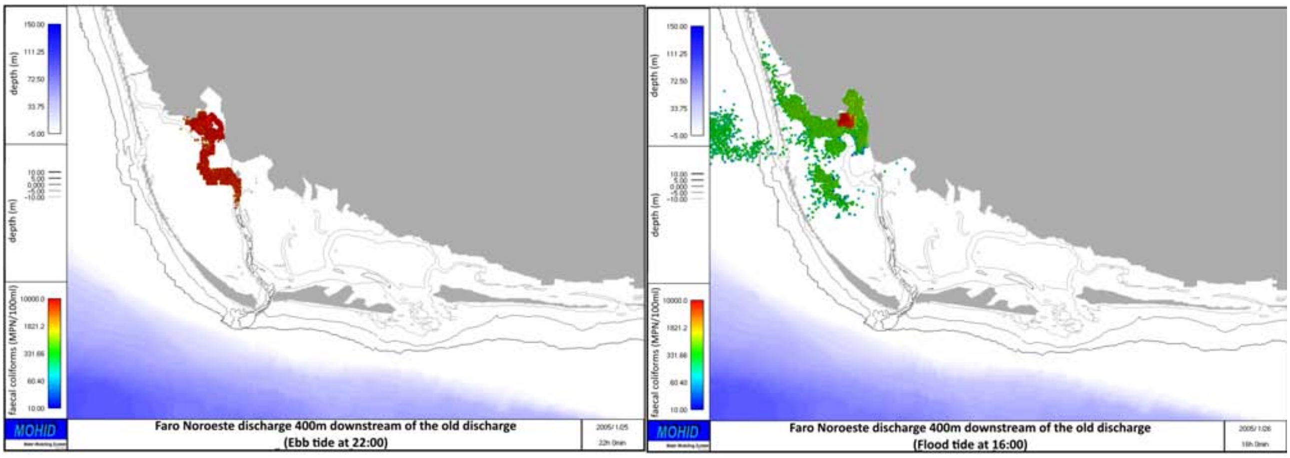

Figure 4.9.
Faecal coliform plumes simulated for a discharge with a concentration of 1×10^4 MPN/100 ml, 400 m downstream of the old discharge.

For this scenario the contamination situation is not very different from the old discharge situation, since in both scenarios there is a large amount of plume that is confined to the WWTP region. However, under conditions of high solar radiation (during the day) the concentration of the coliform plumes drops significantly due to increased inactivation. In the flood tide, although the concentration is lowered by the action of the dilution, the contamination is transported to a larger area. There is also a higher transport of the coliform plume towards the Ancão, with the discharge at 400 m, compared to the current situation, especially in flood tide.
In the Faro Noroeste region the microbiological field campaigns show that the concentrations are between the maximum recommended and limit values or even below the maximum recommended for all points outside the discharge channel. This shows that the dilution and inactivation in this region is sufficient to ensure good water quality by the bathing criteria. Also, coliform accumulation in molluscan shellfish is function of the distance from the discharge and the number of hours of contact with the discharged plume in each tidal cycle (Martins et al., 2006). In the discharge channel the concentrations are high, which is not surprising because in low-water conditions the collected samples have only effluent, without any dilution. The results of the modelling allow to identify the circulation pattern in this region. It was shown that during the ebb tide drainage is mainly through the Faro channel and during the flood tide the water of the Faro channel flows to the region of Montenegro through Esteiro Largo and to the West region through the Ramalhete. This circulation causes the WWTP plume to have a greater influence in the Faro channel during the ebb, while Ramalhete and esteiro Largo are more influenced during flood tide.

4.4. Faro/Olhão Intermunicipal WWTP

The new Faro/Olhão WWTP was built at the site of the old Faro Nascente WWTP, about 2 km east of Faro, included in the ria Formosa area. It has a treatment capacity of 113,200 habitants, 28,149 m^3/day in the year of 2033. This WWTP treats a large part of the wastewater generated in the city of Faro, treated in the old Faro Nascente WWTP, and the wastewater generated in the city of Olhão, treated at the old Olhão Poente WWTP.
The construction of the new WWTP allowed the deactivation of the existing lagoon systems in both facilities, which are inadequate regarding the quality levels required for the treated effluent to be discharged, and which are also undersized by current (qualitative and quantitative) inflow conditions.

The treatment line of the liquid phase consists of complete pre-treatment, homogenization and flow equalization, intermediate pumping, biological treatment according to the Nereda® process, filtration and disinfection. The sludge line comprises gravimetric thickening, and centrifugal dewatering with storage of dehydrated sludge in storage towers.

4.4.1. System hydrodynamics

The results from the simulations obtained for the hydrodynamics of the system are presented in Figure 4.10. The tide situations presented correspond to the extreme conditions of flow in the study area.

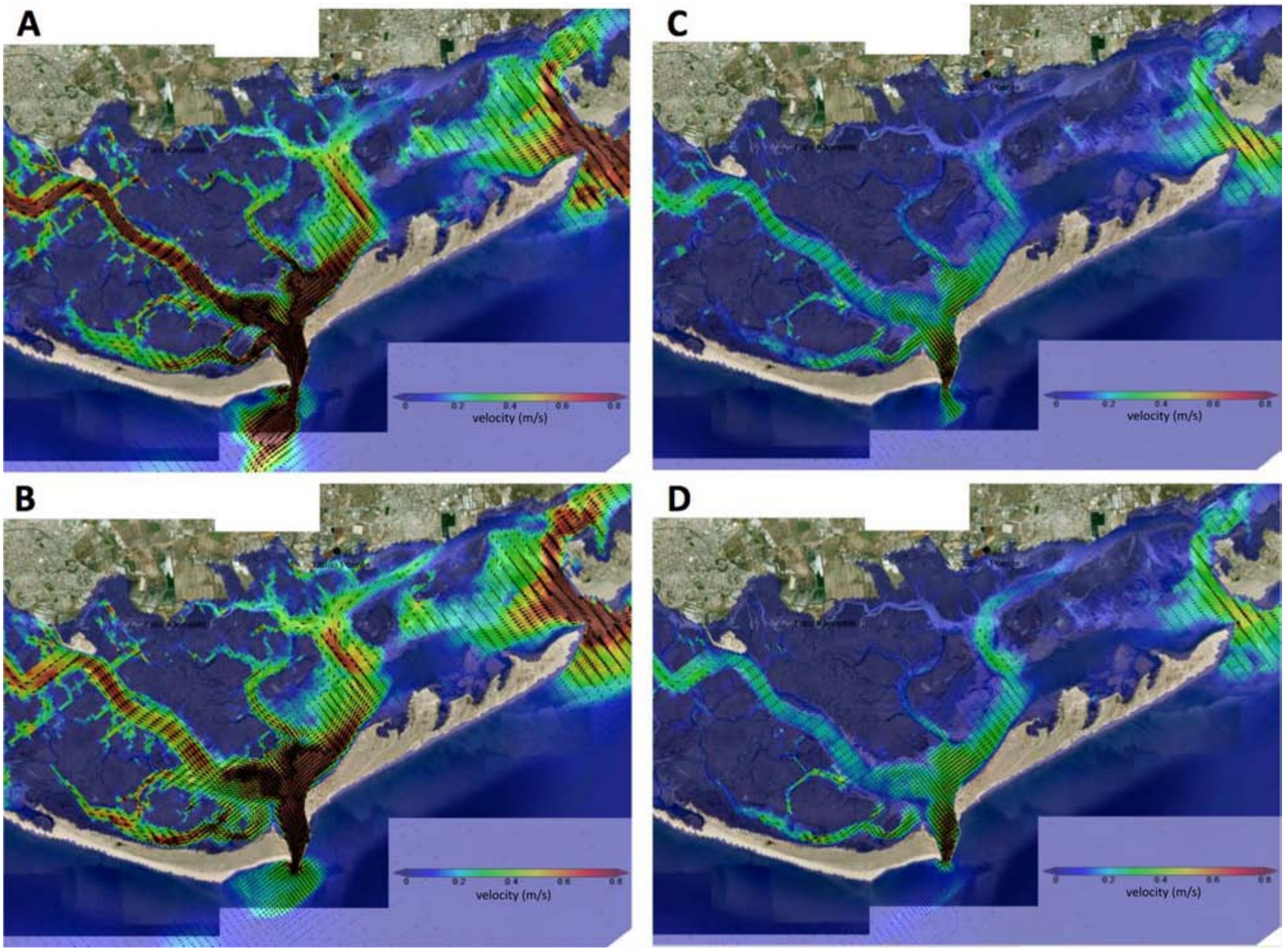

Figure 4.10.
Transient velocity fields for the study area. A – Spring tide, Ebb; B – Spring tide, Flood; C – Neap tide, Ebb; D – Neap tide, Flood.

The highest speeds are found in the bars, Faro channel and the Olhão channel. This situation is similar to the one encountered in the Faro Noroeste results. In these locations the transport is more efficient, giving short residence times. In the channel where the Faro Nascente WWTP discharge is located, the flow in Spring tide presents velocities close to 0.2 m/s both in flood and in ebb. In Neap tide conditions the velocities in the channel are very low, suggesting high residence times in this zone during this tide situation. On the other hand, Olhão Poente WWTP is located in a more hydrodynamically active zone, where speeds between 0.2 and 0.3 m/s are observed in Spring tide and close to 0.1 m/s in Neap tide. Overall, there is a generalized difference in velocities between Spring and Neap tide conditions, as expected, while maintaining the same flow pattern.

4.4.2. Waste water plumes

The simulation of faecal coliform plumes was performed for the various discharge scenarios considering three concentrations of coliforms in the discharge, 1×10^4, 2×10^3 and 300 MPN/100ml for the new Faro/Olhão WWTP. The following results were obtained for Spring and Neap tide scenarios, and for a low tide at night and high tide during the day. These periods are, respectively, where the highest and lowest concentrations in the simulated scenarios were observed due to the hydrodynamic conditions and variation of the inactivation rate of the coliforms with the solar radiation.

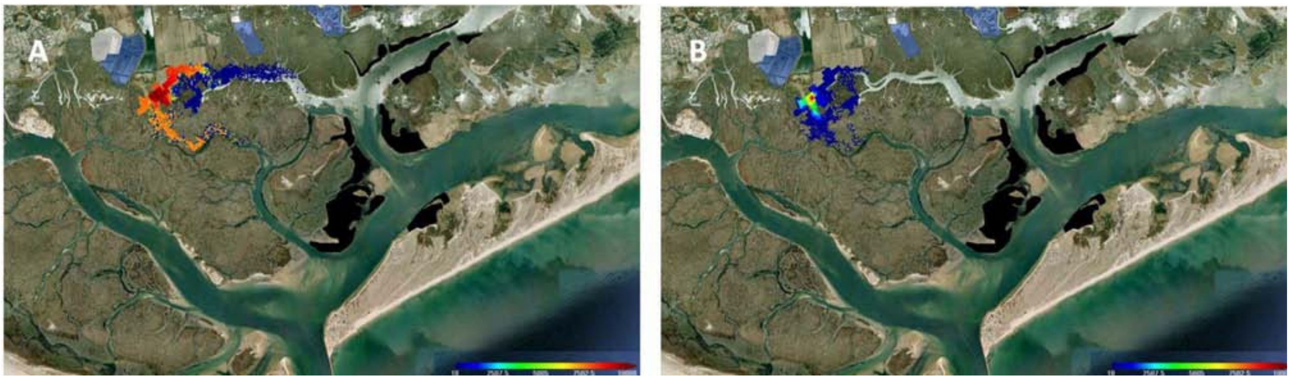

Figure 4.11.
Microbiological plume obtained in the period of Neap tide for the discharge in Faro/Olhão. Concentration of the discharge equal to 1×10^4 MPN/100 ml. A) Night with low tide conditions; B) Day with High tide conditions.

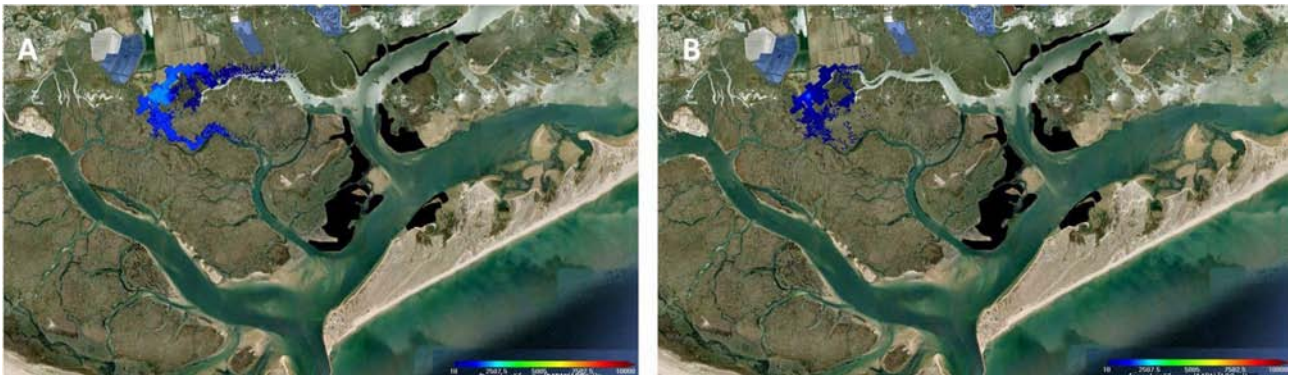

Figure 4.12.
Microbiological plume obtained in the period of Neap tide for the discharge in Faro/Olhão. Discharge concentration equal to 2×10^3 MPN/100 ml. A) Night with low tide conditions; B) Day with High tide conditions.

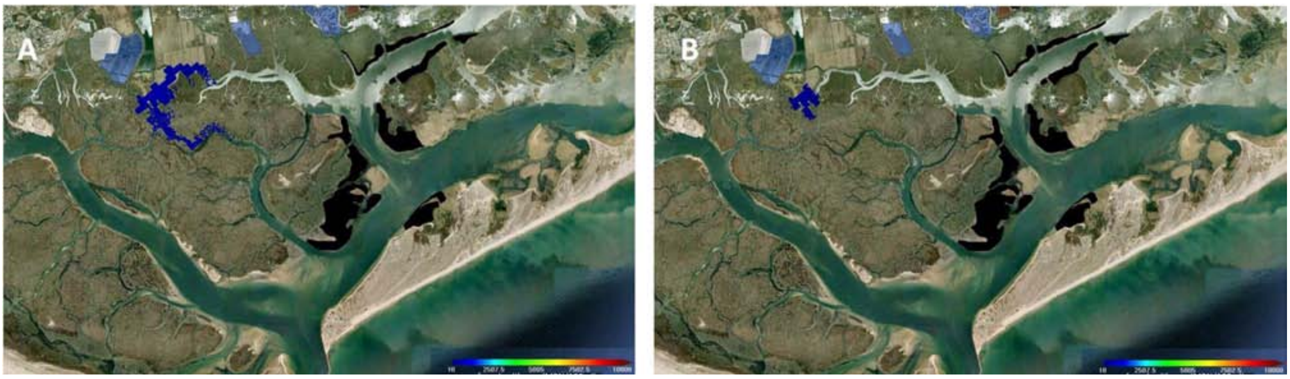

Figure 4.13.
Microbiological plume obtained in the period of Neap tide for the discharge in Faro/Olhão. Discharge concentration equal to 300 MPN/100 ml. A) Night with low tide conditions; B) Day with High tide conditions.

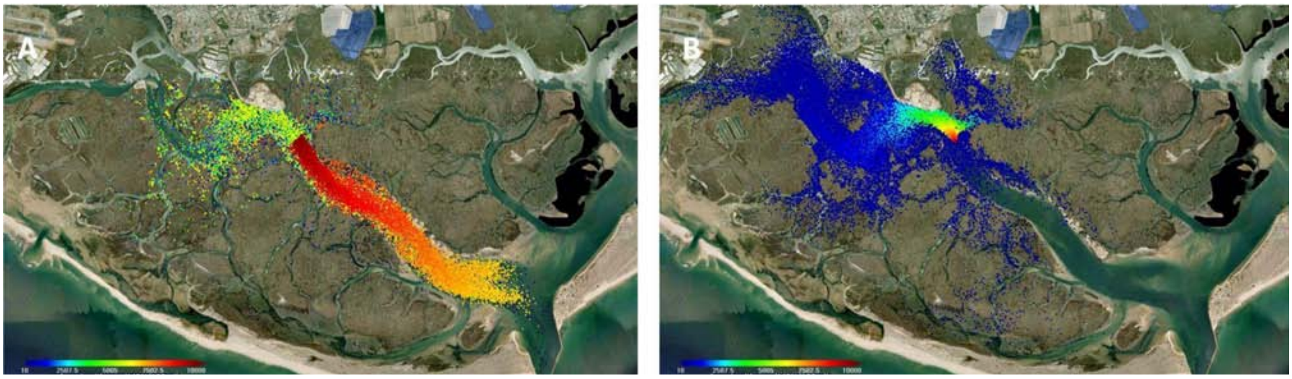

Figure 4.14.
Microbiological plume obtained in the period of Neap tide for the discharge in Faro Channel. Concentration of the discharge equal to 1×10^4 MPN/100 ml. A) Night with low tide conditions; B) Day with High tide conditions.

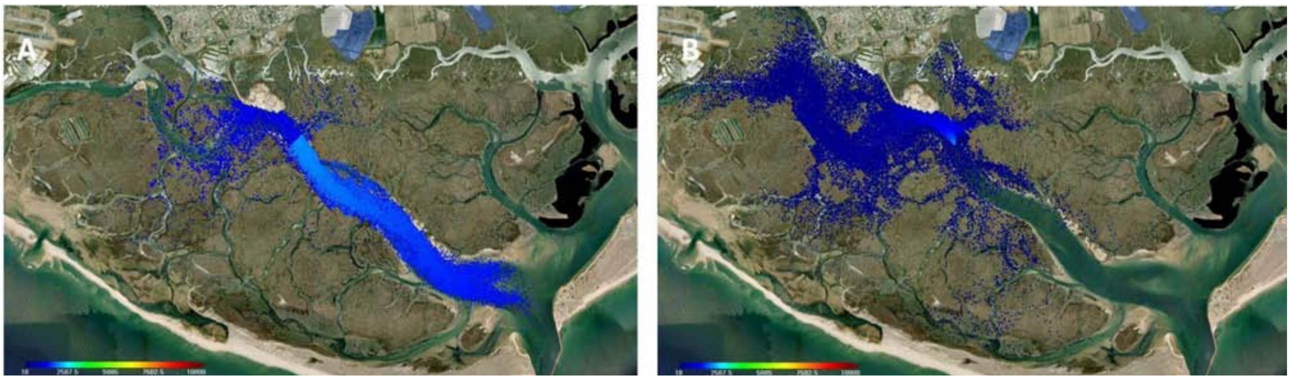

Figure 4.15.
Microbiological plume obtained in the period of Neap tide for the discharge in Faro Channel. Discharge concentration equal to 2×10^3 MPN/100 ml. A) Night with low tide conditions; B) Day with High tide conditions.

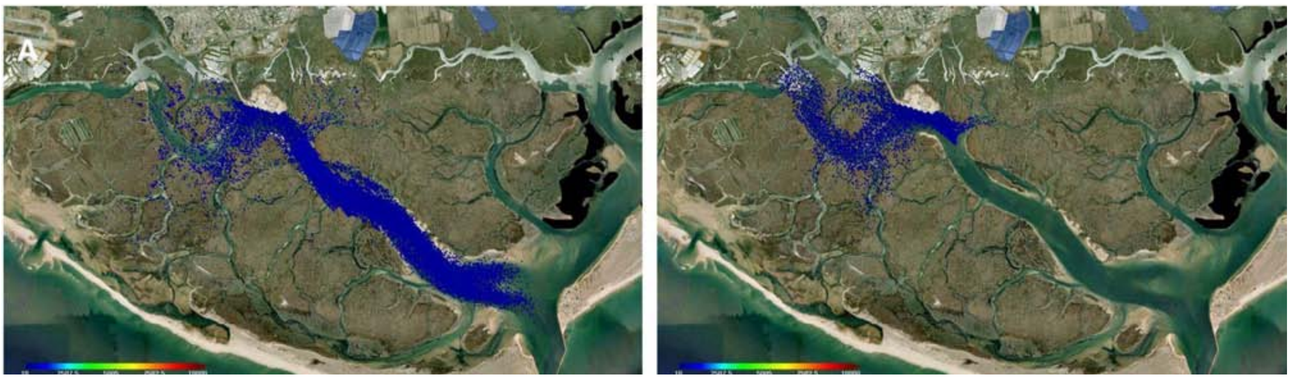

Figure 4.16.
Microbiological plume obtained in the period of Neap tide for the discharge in Faro Channel. Discharge concentration equal to 300 MPN/100 ml. A) Night with low tide conditions; B) Day with High tide conditions.

For the Neap tide scenario, the microbiological plume associated to the discharge in Faro/Olhão is maintained confined to the channel where the discharge is carried out and to the channel immediately to the south, for both tide conditions. In terms of concentrations there is a clear difference between the day and night situation due to the inactivation of faecal coliforms associated with solar radiation. As the concentration of coliforms in the discharge is reduced the area of influence of the plume also decreases, especially at high tide during the day. For the location of the discharge in the Faro Channel, it could be thought, in the first analysis, that the microbiological impact was lower due to the greater dynamics and

mixing capacity of the discharge point. Unlike salinity, the concentration of faecal coliforms is not a conservative property due to its inactivation, that is, a conservative property here is understood as that of a property that in its transport is subject to advection and diffusion but has no processes of destruction or creation (sinks and sources). This fact puts two antagonistic processes in presence when the microbiological load is discharged in a region of high dynamics: on one hand, the greater dynamics produces a greater diffusion, lowering the concentration, but on the other hand, this same dynamic does not give time to the inactivation occurs before the plume spreads over a larger area of Ria Formosa. On the contrary, a discharge in a confined area such as that of the current Faro Nascente WWTP, produces higher local concentrations due to less diffusion but restricts the affected region, giving time for the plume to inactivate before being dispersed to other regions.
For discharges into the Faro Channel at low water, the plumes spread in the area adjacent to the discharge zone, as well as throughout the channel downstream near the Faro Ria Formosa exit. At high water, the plume is transported upstream of the discharge, and spreads over a larger area due to rising water levels during this tide situation. During the flood some particles are retained downstream of the discharge into small existing channels and are then transported again during the ebb. In concentrations terms, as in the case of Faro/Olhão, there is a clear difference between the day and night situation, due to the faecal coliform mortality associated with solar radiation. As the concentration of coliforms in the discharge is reduced this area also decreases, especially at high tide during the day, in which the area of the plume is substantially reduced.
For Spring tide, the main difference compared to the Neap tide is the extension of the coliforms plume, which, as expected, extends over a larger area due to the increase of the submerged zones and the greater dynamics of the system.

Figure 4.17.
Microbiological plume obtained in the period of Spring tide for the discharge in Faro/Olhão. Concentration of the discharge equal to 1×10^4 MPN/100 ml. A) Night with low tide conditions; B) Day with High tide conditions.

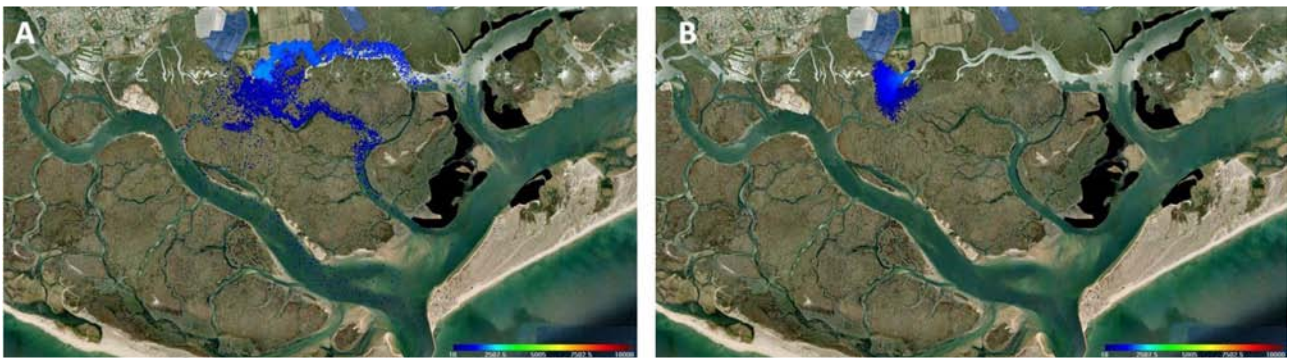

Figure 4.18.
Microbiological plume obtained in the period of Spring tide for the discharge in Faro/Olhão. Concentration of the discharge equal to 2×10^3 MPN/100 ml. A) Night with low tide conditions; B) Day with High tide conditions.

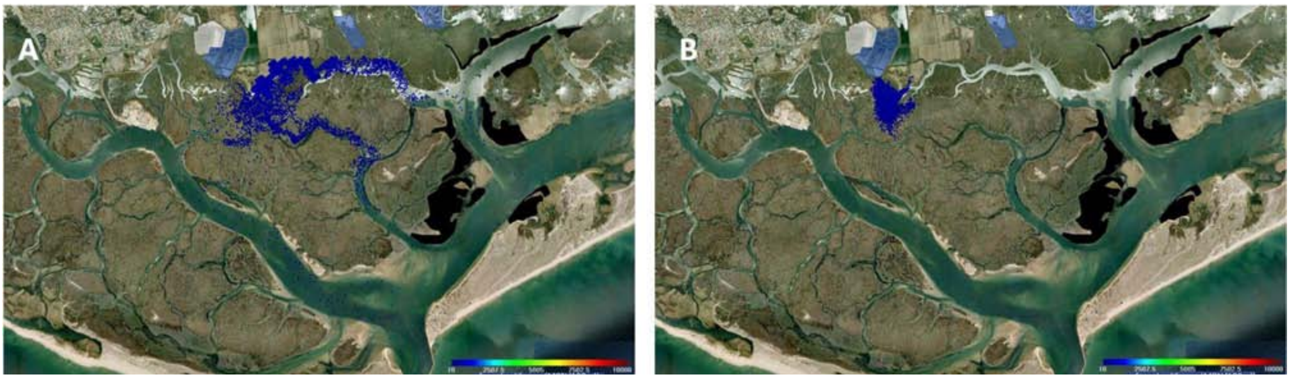

Figure 4.19.
Microbiological plume obtained in the period of Spring tide for the discharge in Faro/Olhão. Concentration of the discharge equal to 300 MPN/100 ml. A) Night with low tide conditions; B) Day with High tide conditions.

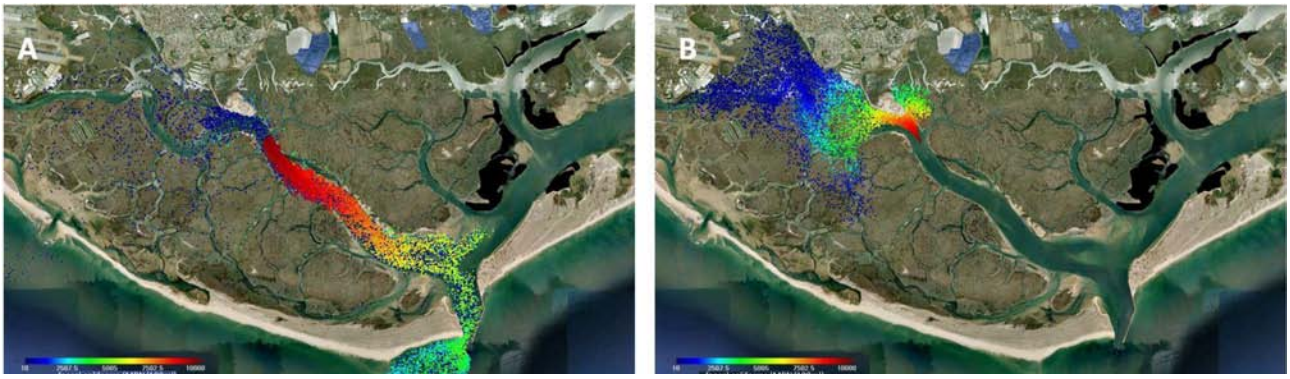

Figure 4.20.
Microbiological plume obtained in the period of Spring tide for the discharge in Faro Channel. Concentration of the discharge equal to 1×10^4 MPN/100 ml. A) Night with low tide conditions; B) Day with High tide conditions.

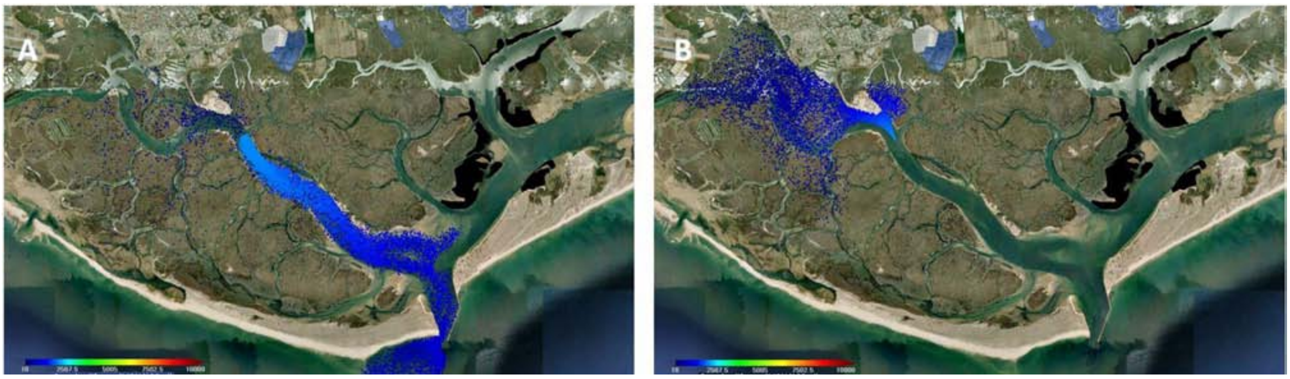

Figure 4.21.
Microbiological plume obtained in the period of Spring tide for the discharge in Faro Channel. Concentration of the discharge equal to 2×10^3 MPN/100 ml. A) Night with low tide conditions; B) Day with High tide conditions.

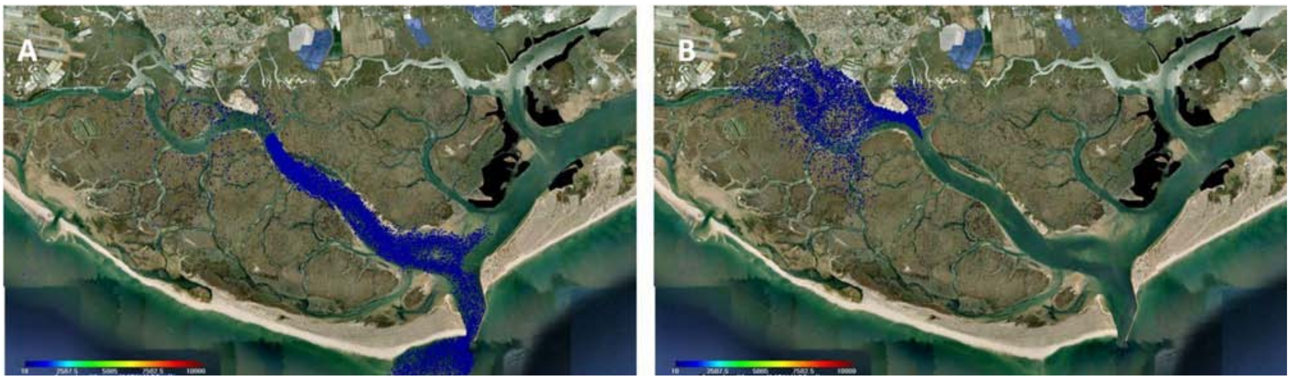

Figure 4.22.
Microbiological plume obtained in the period of Spring tide for the discharge in Faro Channel. Concentration of the discharge equal to 300 MPN/100 ml. A) Night with low tide conditions; B) Day with High tide conditions.

In Spring tide scenario, at low tide the plume associated with the discharge in Faro/Olhão is less confined, leaving either the channel where the discharge is located, or the channel to the south, entering through the Olhão channel and the Faro channel. At high tide, the plume is again confined to the area surrounding the discharge and is even more confined than in the same situation but in Neap tide scenario. This is because, in a Neap tide scenario, the flow of flood water cannot counter the direction of the discharged water flow, thus creating a larger zone regarding the dispersion of the particles, since they can enter the channels adjacent to the discharge, being more easily transported away from the discharge. During the Spring tide scenario, the flood flow is strong enough to change the direction of the upstream discharge flow, creating a physical containment barrier for the plume and preventing the particles from entering the channels south of the discharge. In concentrations terms, there is a clear difference between the day and night situation due to solar radiation. As the concentration of coliforms in the discharge is reduced the area of influence of the plume also decreases.
Considering the location of the discharge in the Faro Channel at low tide, the plume associated with the discharge is transported out of the Barra de Faro / Olhão, due to the increase of the current in the Faro Channel during ebb in Spring tide. This increase in current velocity also reduces the scattering of the particles in the area adjacent to the discharge, channeling all particles through the Faro Channel. During the flood, many of the particles that are in the vicinity of Barra de Faro / Olhão are transported not only along the Faro Channel, but also along the Olhão Channel, spreading in the vicinity of this. Dependent on the time on which the ebb/flood tide inversion occurs (night or day), the particles carried by the Olhão Channel tend to remain (more or less) time in that zone before being inactivated by solar radiation. At high tide, the area of influence of the plume associated with the discharge is similar to that described for the Neap tide scenario.

Final remarks

In the region associated to the Almargem WWTP, the mathematical model allowed to predict that with entry in service of the Almargem WWTP and the decommissioning of the old Tavira WWTP the fecal coliform concentrations in the Gilão River will decrease substantially. The Impact in the Almargem water stream was only moderate, however, since the discharge regulations limits for the new WWTP are 2,000 MPN/100ml of faecal coliforms and therefore, overall, the microbiological contamination inside the Ria Formosa would decrease. The simulations with several alternative locations for the discharge in the Almargem River and the Cabanas Channel showed that the discharge in the middle of the Almargem Channel is more advantageous, being the plume confined to the interior region of the Almargem Channel

and does not affect in any way the bar or the bathing waters regions. The downstream discharge locations progressively aggravate the bacterial concentration in the areas closest to the bathing waters.
In the Faro/Olhão region, in relation to hydrodynamics of the system there are significant differences of speeds when considering a neap tide situation or a spring tide situation, however the flow pattern is the same. The highest speeds are found in the bars, in the main channel of Faro and in the main channel of Olhão, resulting in shorter residence times in these zones, however, in the channel where the discharge of Faro/Olhão WWTP is located, the flow in neap tide situation presents very low channel velocities, which suggests high residence times in this area during this tide situation. This fact conditions the impact in terms of salinity produced by the discharge of fresh water. Salinity is a conservative property, which is why its concentration depends only on the dilution capacity of the system. Thus the discharge of fresh water into the main channel does not have any significant impact on the region surrounding the discharge due to the high dilution capacity produced by the flow in that area.
Unlike salinity, microbiological contamination is not a conservative property. The faecal coliforms concentration used as an indicator for this contamination depends not only on the dilution of the system but also on the inactivation, which is mainly due to the effect of solar radiation, as well as to saline shock and the effect of temperature. This shows that the regions with the greatest dilution capacity dont always match to those in which the impact of the microbiological discharge is better. This fact is notorious in this study, where more confined regions of microbiological plumes where obtained, although with higher maximum concentration values, in the case of discharge in Faro\Olhão compared to what happens for the discharge in the Faro Channel. This is due to the greater dynamics in the Faro channel that transports the contaminated water through the system very quickly, before it has time to be inactivated.
Studies conducted at the Ria Formosa over the last years concerning WWTP discharges allowed the global characterization of the ecosystem in terms of anthropogenic influence and trophic activity of the study areas and in the development of models that describe the processes that impact the water quality in these places. The studies were able to respond to short-term issues - support for the remodelling / construction of WWTP and the assessment of their environmental impact in the receiving environment - and issues expected in the medium term, namely those arising from the Portuguese authorities' obligations to the European Union due to the application of directives related to waste water (Water Directive, Bathing Water Directive and Urban Waste Water Treatment Directive and Water Directives for Shellfish Use).

References

Allen C.M., 1982. Numerical simulation of contaminant dispersion in estuary flows. *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 381(1780):179-194.

Davis, M., 2010. Water and Wastewater Engineering: Design Principles and Practice. McGraw-Hill Education, New York.

Dias, J. M., Sousa, M. C., Bertin, X., Fortunato, A. B., Oliveira A., 2009. Numerical modeling of the impact of the Ancão Inlet relocation (Ria Formosa, Portugal). *Environmental Modelling & Software* 24(6):711-725.

IMAR, 2012. Framework for Ria Formosa Water Quality, Aquaculture and Resource Development. IMAR.

MARETEC, 2018. MOHID. Online available at: http://www.mohid.com

Martins, F., Leitão, P., Silva, A., & Neves, R., 2001. 3D modelling in the Sado estuary using a new generic vertical discretization approach. *Oceanologica Acta* 24(1):51-62.

Martins, F., Pina, P., Calado, S., Delgado, S., & Neves, R., 2003. A coupled hydrodynamic and ecological model to manage water quality in Ria Formosa coastal lagoon. *Advances in Ecological Sciences* 18:93-100.

Martins, F., Reis, M., Neves, R., Cravo, A., Brito, A. & Venâncio, A., 2006. Molluscan Shellfish bacterial contamination in Ria Formosa coastal lagoon: A modelling approach. *Journal of Coastal Research* 39:1551-1555.

Neves, R. & Martins, F., 1996. Modelação Lagrangeana dos Processos de Transporte na Ria Formosa. 5ª Conferência nacional sobre a qualidade do ambiente, Aveiro, Portugal.

Neves, R., Leitão, P., Braunschweig, F., Coelho, H., Martins, F., Santos, A., & Miranda, R., 2000. The advantage of a generic coordinate approach for ocean modelling. *Water Studies* 7:25-34.

Zhao, L., Chen, Z., & Lee, K., 2011. Modelling the dispersion of wastewater discharges from offshore outfalls: a review. *Environmental Reviews* 19: 107-120.

5. Role of microbes in the Ria Formosa lagoon

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5.1. What is role of microbes in C fluxes in the sea?

With the development of epifluorescence microscopy and sensitive radioisotope techniques, high abundance and activity of microorganisms was observed in marine waters since 1970s and 1980s. These observations resulted in a new concept of rapid turn-over and recycling of organic matter through a 'microbial loop' (Azam et al., 1983; Azam, 1998). Figure 5.1 illustrates fluxes of material through the marine microbial loop. Main processes are C fixation by photosynthetic microorganisms (prokaryotic and eukaryotic) with exudation losses of Dissolved Organic Matter (DOM), which is incorporated by heterotrophic bacteria. Phagotrophic protists in turn graze both autotrophs and bacteria producing 'sloppy feeding' loss of DOM, which returns to the loop. DOM is remineralized by all microorganisms into Dissolved Inorganic Nutrients (DIN), which are taken up by autotrophic and heterotrophic microorganisms. Thus, bacteria and the whole microbial loop function as a dynamic sink for C and monopolizes > 90% of C fixed by primary production in Ria Formosa waters (Ducklow et al., 1986; Pomeroy et al., 2007). The role of marine viruses still remains to be completely elucidated in the oceans, although it is known that viral lyses promotes biogeochemical fluxes by releasing both dissolved (DOM) and also particulate organic matter (POM) from lysed cells (Suttle, 2007). In Figure 5.1, viruses are depicted to produce mainly DOM, which is directly absorbed by bacteria, since the POM fraction is much smaller and has to be subjected to exoenzymatic hydrolysis into DOM by bacteria before incorporation.

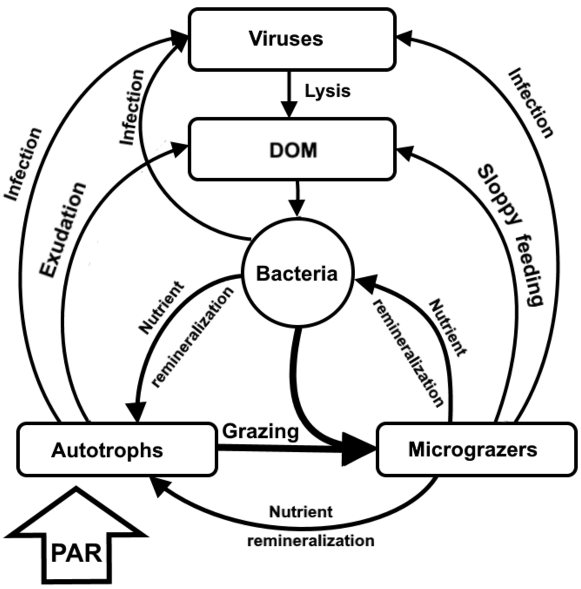

Figure 5.1.
Diagram of microbial loop illustrating concept of dynamic carbon sink. DOM: Dissolved Organic Matter; PAR: Photosynthetically Active Radiation.

5.2. Phytoplankton community in the Ria Formosa lagoon

Phytoplankton constitutes a community of photosynthetic microorganisms drifting in surface waters and span size ranges from 0.2 to 230 µm (see Box 5.1). They generate more than half the oxygen in the earth s atmosphere and constitute the base of all aquatic/marine foodwebs in surface waters.

Box 5.1. What are size ranges of microbial plankton?

There are 4 size-classes of microscopic plankton:

1. Ultra- or virioplankton (< 0.2 µm): viruses and very small bacteria
2. Picoplankton (0.2 - 2 µm): heterotrophic and autotrophic (photosynthetic) bacteria
3. Nanoplankton (2 - 20 µm): heterotrophic and autotrophic nanoflagellates, small diatoms
4. Microplankton (20 - 200 µm): diatoms, dinoflagellates, ciliates

The Ria Formosa lagoon (Fig. 5.2), located on the Atlantic ocean in the Algarve region of Portugal, is the most south-westerly of European lagoons. In contrast to microtidal conditions in most Southern European lagoons, the Ria has a mesotidal regime with a tidal range varying between 1.3 m at neap and 3.4 m at spring tides. This shallow network of saltmarsh, sediment flats and tidal channels covers an area of 58 km^2, and is an internationally recognized site of ecological importance (Newton et al., 2014), as well as supporting a fishery and aquaculture industry of national significance.

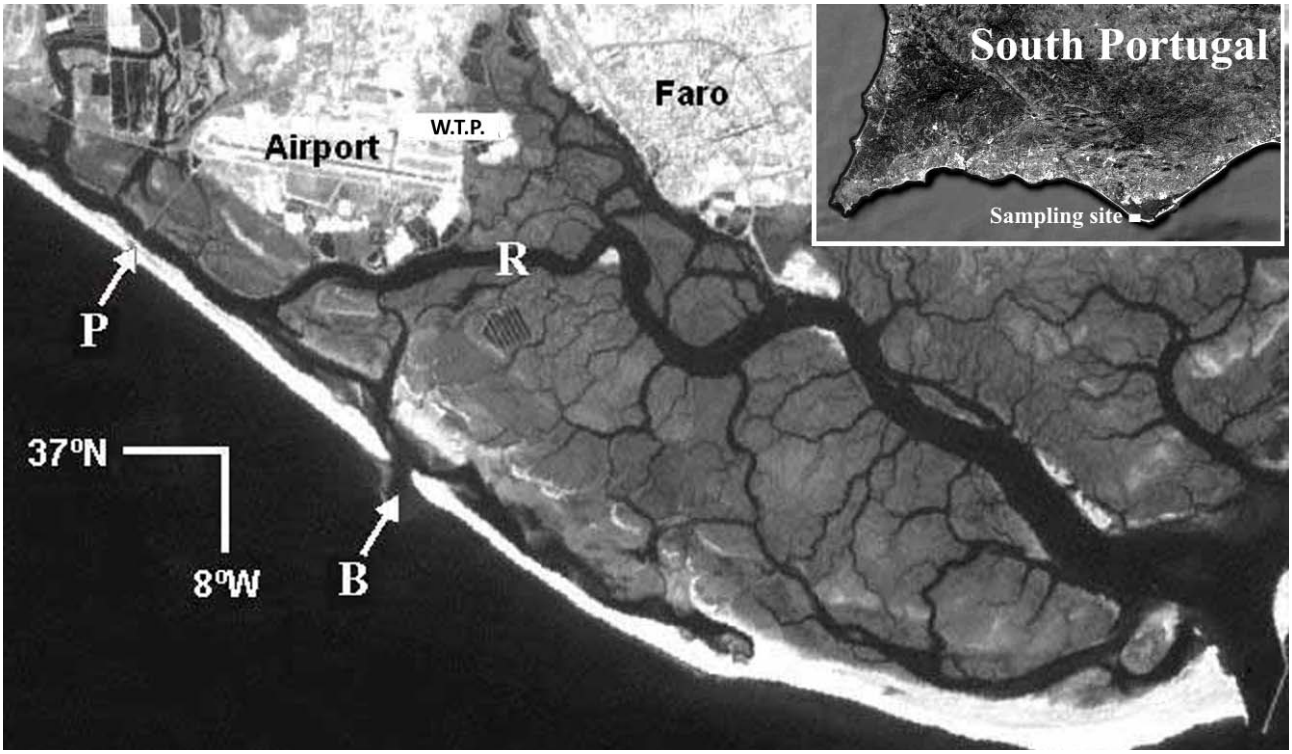

Figure 5.2.
Location of sampling stations (P: Ponte; B: Barra; R: Ramalhete) in the western region of the Ria Formosa. WTP: urban waste water treatment plant.

This study presents data on pelagic primary and bacterial production, as well as phytoplankton community structure at three stations representing contrasting situations within the lagoon, namely: an artificial inlet opened in 1997 prior to this study (B in Fig. 5.2), a channel draining salt marsh (P in Fig.

5.2), and a channel draining both salt marsh (R in Fig. 5.2) and the effluent from the main facility for urban Water Treatment Plant (WTP in Fig. 5.2) of Faro. The new outlet to the ocean (station B) changed hydrodynamics in Ria Formosa substantially (see Newton & Icely, 2002 for details). The sampling strategy was designed to assess microbial dynamics during extreme tidal conditions over the year. These conditions occur for neap tides close to Summer (June) and Winter (December) solstice and for spring tides during Autumn (September) and Spring (April) equinox.

Sampling campaigns were carried out on 13th June 2001, 18th September 2001, 8th December 2001 and 27th April 2002 (Table 5.1). A fifth campaign was added on 3rd July 2002 for phytoplankton microscopy enumerations. Water samples were collected during daylight at high water (HW), mid - ebb (EBB), low water (LW), and mid-flood (FLOOD) from Barra, Ponte and Ramalhete stations (B, P and R in Fig. 5.1) in the Ria Formosa. Water samples for bacterial and phytoplankton enumeration were preserved with particle-free 25% gluteraldehyde (2% final concentration) and kept refrigerated and processed within 24 h to minimize cell loss. Samples were filtered through 0.2 µm black polycarbonate filters mounted on 0.45 µm cellulose acetate backing filters and stained with 4 ,6-diamidino-2-phenylindole (DAPI) for 5 minutes (JGOFS 1994). Sample volumes of 2 ml were filtered for picoplankton and 20 ml for nanoplankton and small microplankton. Filters were mounted on a slide with Cargille type A non-fluorescent immersion oil and frozen until examination. DAPI was used as a fluorochrome dye and samples were observed with a Leica epifluorescence microscope using UV and blue filters for DAPI and for chlorophyll autofluorescence, respectively. The concentration of chlorophyll *a* (chl *a*) and pheopigments (pheo) in the water samples was determined fluorimetrically within days after sampling, following methods described in JGOFS (1994).

In microscope enumerations, phytoplankton cells were separated in two size fractions: 0.2-2 µm – picoplankton (cyanobacteria and picoflagellates) and 2-200 µm – nanoplankton and small microplankton (nanoflagellates, dinoflagellates, diatoms and some autotrophic ciliates). Cells were identified according to the following features: cyanobacteria – orange dots (< 2 µm diameter) under blue light; small flagellates – larger blue dots (nucleus ~1-2 µm diameter) surrounded by a paler blue halo (cytoplasm 3-10 µm diameter) under UV light and with orange/red aufluorescence under either UV or blue light; nanoflagellates and dinoflagellates (2-100 µm) – shapes, presence of chloroplasts and flagella (when visible); diatoms – shape, chloroplasts and frustules; ciliates – shape, presence of chloroplasts and cilia (when visible). At least 20 random fields of view were counted for each size fraction. Cell volumes for biomass determination were determined following formulas given in Box 5.2.

To determine Total Bacteria Number (TBN) and Bacterial Biomass (BB) compiled in Table 5.2, a minimum of 300 heterotrophic bacteria (without autofluorescence) and 25 fields of view

Box 5.2. How is phytoplankton cell volume and carbon determined?

Biovolumes were calculated on the basis of pre-defined 3-dimensional shapes and their respective stereometric formulas recommended by Hillebrand et al. (1999). Measurements of linear dimensions were made with a calibrated ocular micrometer scale in the microscope eyepiece.

Carbon content (CC) was estimated from mean cell volume (MCV) using following non-linear equations:

- Cyanobacteria and Picoflagellates:
  $CC\ (pgC.Cell^{-1}) = 0.436 \times MCV^{0.863}$
- Nanoflagellates (2-20 µm):
  $CC\ (pgC.Cell^{-1}) = 0.216 \times MCV^{0.939}$
- Diatoms:
  $CC\ (pgC.Cell^{-1}) = 0.288 \times MCV^{0.811}$
- Dinoflagellates:
  $CC\ (pgC.Cell^{-1}) = 0.760 \times MCV^{0.819}$

Total biomass was then calculated by multiplying CC with abundance.

were counted. Cell dimensions of 50 randomly selected bacteria were measured in each sample with a New-Porton calibrated graticule (Graticules Ltd.). Cell carbon content and biomass were calculated individually with the carbon to volume allometric relationship derived by Norland (1993).
Total phytoplankton enumerated microscopically averaged 23 000 x 10^3cells L^{-1} at HW and 12 000 x 10^3cells L^{-1} at LW at all stations. Phytoplankton abundance showed significant differences between HW and LW. Lowest abundance occurred in December 2001 with 2700 x 10^3cells L^{-1} at Ponte during HW and with 2400 x 10^3cells L^{-1} at Barra during LW. Highest abundance was observed in July 2002 with 78 000 x 10^3cells L^{-1} at Barra during HW and 29 000 x 10^3cells L^{-1} at Ponte during LW. Figure 5.3 shows that seasonal fluctuations in phytoplankton abundance were not as marked as in chlorophyll *a* and phaeopigments, when pigment concentrations in winter were less than half of that in summer.

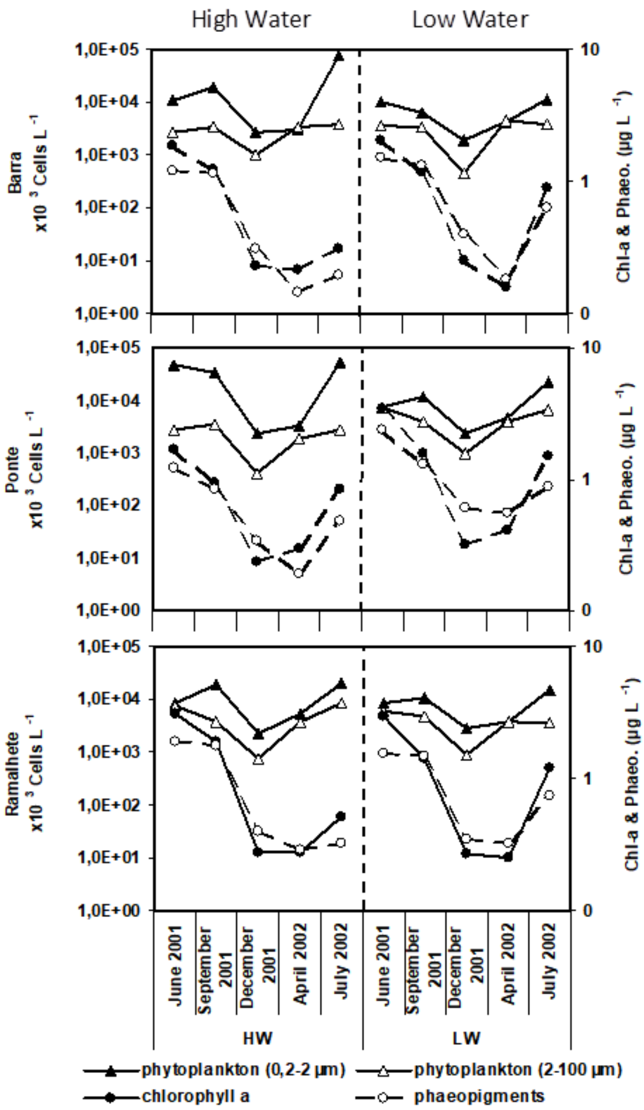

Figure 5.3.
Seasonal variations in photopigment concentrations and abundance of two main phytoplankton size- fractions at the three stations. Note Log scale in y-axes.

Variations in abundance of different phytoplankton groups are depicted in Figure 5.4. Cyanobacteria were the most numerous organisms at all sites ranging from a mean of 22 300 x10^3cells.L^{-1} (HW-Ponte) to 5 300 x10^3cells.L^{-1} (LW-Barra). Pico- and nanoflagellate abundance ranged from 5 100 x10^3cells.L^{-1} (HW-Ponte) to 1 200 x10^3cells.L^{-1} (LW-Ramalhete) for picoflagellates, and from 27 00 x10^3cells.L^{-1} (LW-Ponte) to 1 300 x10^3cells.L^{-1} (HW-Ponte) for nanoflagellates. At both HW and LW, picoflagellates were more numerous than nanoflagellates at Ponte, but were less numerous at Barra and Ramalhete. Diatoms varied between 2 400 x10^3cells.L^{-1} (HW-Ramalhete) and 480 x10^3cells L^{-1} (HW-Barra). Dinoflagellates and ciliates were the least abundant taxa, ranging between 260 x10^3cells.L^{-1} (HW-Barra) and 110 x10^3cells.L^{-1} (LW-Ramalhete) and between 120 x10^3cells.L^{-1} (HW-Ramalhete) and 50 x10^3cells.L^{-1} (HW-Barra or Ponte), respectively. Overall variability was higher at HW than LW for cyanobacteria, picoflagellates, dinoflagellates and ciliates, but not for nanoflagellates and diatoms, which varied more at LW. Typical seasonal fluctuations in phytoplankton groups can also be seen in Figure 5.4 with decreasing numbers in winter and increasing during spring-summer, particularly for cyanobacteria and picoflagellates. Both dinoflagellates and ciliates occurred generally in low numbers without any evident seasonal or spatial pattern. Comparison of seasonal abundance of phytoplankton taxa and photopigments (chl) revealed generally good correlations at all 3 stations ($n = 10$; $r \geq 0.76$; $p<0.05$), whereas diatoms appeared better correlated with phaeopigments (eg. Ponte: $n = 10$; $r = 0.82$; $p<0.01$).

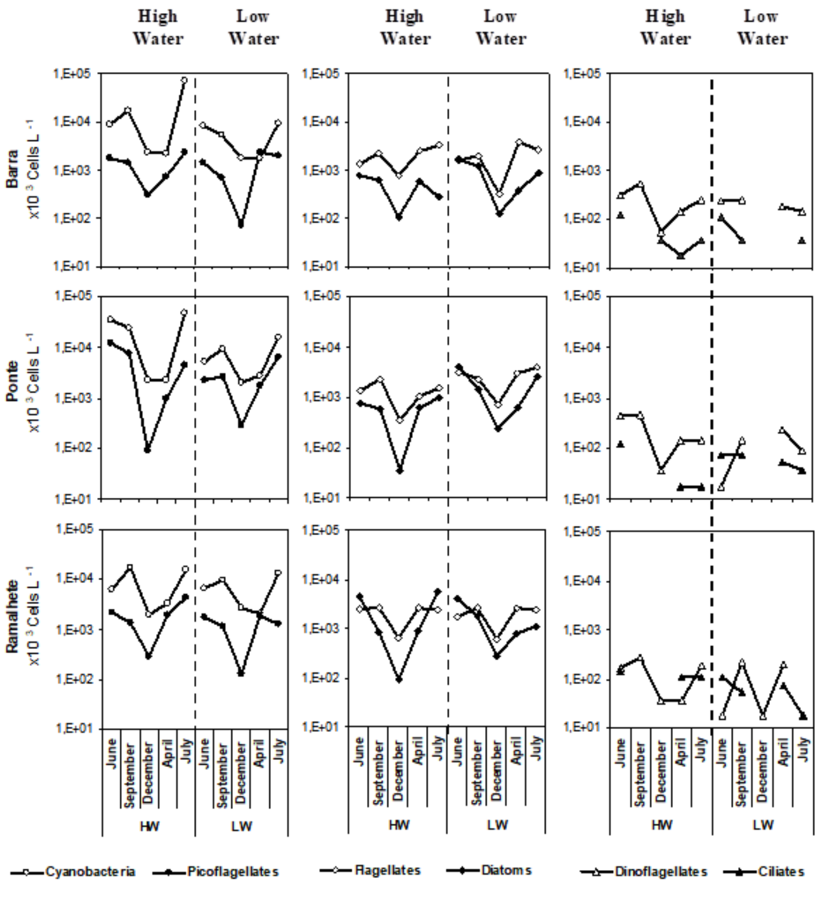

Figure 5.4.
Seasonal variations in different phytoplankton groups at the three stations. Note Log scale in y-axes.

Mean biomass of different phytoplankton groups are presented in Table 5.1. Total phytoplankton biomass throughout the sampling period averaged 158 µgC. L^{-1} during HW and 318 µgC.L^{-1} during LW. Minimum phytoplankton biomass was detected in December 2001 with 12 µgC. L^{-1} at Ponte during HW and with 26,19 µgC. L^{-1} at Ponte in April 2002 during LW. Diatoms exhibited highest mean biomass at all stations ranging fom 571 µg C. L^{-1} (LW-Ponte) to 36.5 µgC. L^{-1} (HW-Ponte). Dinoflagellate and nanoflagellate mean biomass values were comparable, ranging from 62.8 µgC. L^{-1} (HW-Barra) to 18.3 µgC. L^{-1} (HW-Ramalhete) for dinoflagellates, and from 52.7 µgC. L^{-1} (LW-Ponte) to 26.4 µgC. L^{-1} (HW-Ponte) for flagellates. Cyanobacteria were always the most abundant group, but due to very small cell sizes, had low mean biomass ranging between 23.2 µgC L^{-1} (HW-Ponte) and 6.4 µgC. L^{-1} (LW- Barra). Picoflagellates exhibited lowest mean biomass with ranges between 5.6 µgC. L^{-1} (HW-Ponte) and 1.2 µgC. L^{-1} (LW-Ramalhete).

Table 5.1.

Mean biomass of different phytoplankton groups (μg L^{-1}) at the three stations for the complete sampling Period (June 2001 to July 2002) during High Water and Low Water tidal stages. Note standard deviations in italics and coefficients of variation in %

	HIGH WATER			LOW WATER		
	BARRA	PONTE	RAMALH.	BARRA	PONTE	RAMALH.
Cyanobacteria	**22.27** *32.99* 148%	**23.22** *19.72* 85%	**9.80** *8.70* 89%	**6.44** *4.63* 72%	**8.24** *7.58* 92%	**8.11** *5.90* 73%
Picoflagellates	**1.37** *0.77* 56%	**5.56** *5.35* 96%	**1.90** *1.79* 94%	**1.21** 0,89 74%	**2.65** *3.05* 115%	**1.22** *0.61* 50%
Nanoflagellates	**39.31** *29.78* 76%	**26.42** *17.58* 67%	**39.88** *21.83* 55 %	**41.67** *25.85* 62%	**52.67** *45.94* 87%	**28.53** *7.72* 27%
Dinoflagellates	**62.78** 54.60 87%	**30.18** *32.29* 107%	**18.35** *25.80* 141%	**40.45** *14.56* 36%	**40.53** *32.68* 81%	**26.52** 11.11 42%
Diatoms	**79.56** *87.41* 110%	**36.56** *46.53* 127%	**78.31** *79.62* 102%	**84.35** *60.05* 71%	**571.31** *1 076.22* 188%	**62.92** *37.63* 60%
TOTAL (g C.L^{-1})	**205.29**	**121.94**	**148.23**	**174.13**	**675.41**	**127.29**

Several trends could be ascertained from microscopical analyses of phytoplankton community, namely:

a) Although overall mean abundance of phytoplankton was much higher during HW (23.0×10^6 cells. L^{-1}) than during LW (12.0×10^6 cells. L^{-1}), mean total biomass was half (158 μgC. L^{-1}) during HW than during LW (318 μgC.L^{-1}) due to abundant and ubiquitous picophytoplankton. This fraction demonstrated high variability which explained the lack of correlation between chlorophyll-derived biomass and microscopy-derived biomass, which resulted in carbon content overestimation of smallest size fraction (0.2-2 μm). In fact, observed biomass was 5.5-fold higher than calculated biomass in this study, resulting in a C:Chl ratio of 275 rather than the classic ratio of 50.

b) Seasonal patterns in phytoplankton community structure included summer blooms of oceanic cyanobacteria

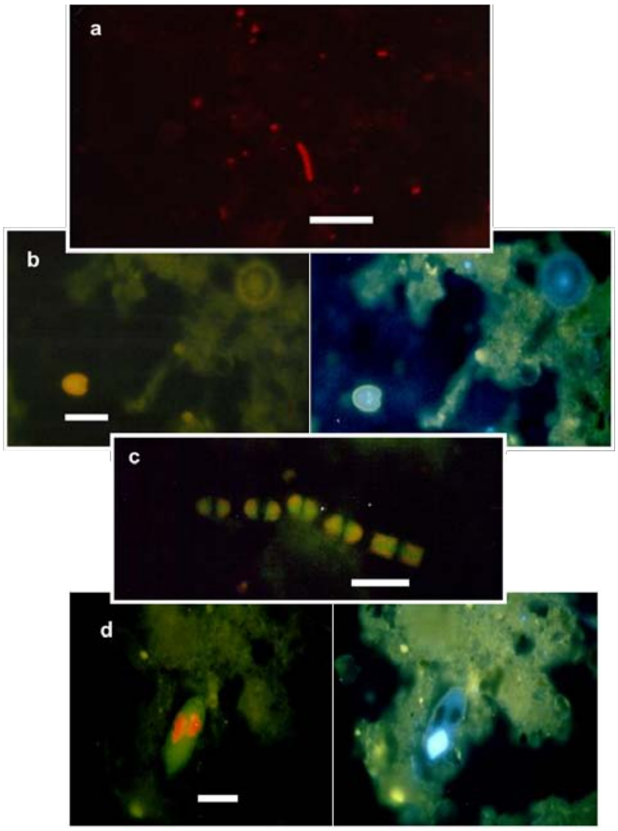

Figure 5.5.

Photomicrographs of pico- and nanophytoplankton taken with epifluorescence microscopy. 5.5.a: orange-red autofluorescence of chroococcoid and short chain-forming cyanobacteria in unstained sample under green light; 5.5.b: autofluorescent nanoflagellate under blue light (left) and stained with DAPI under UV light (right); 5.5.c: autofluorescent Chaetoceros spp. chain under blue light; 5.5.d: autofluorescent dinoflagellate under blue light (left) and stained with DAPI under UV light (right). Bars: 10 μm. Courtesy of Sandra M. Caetano.

(*Synechococcus* spp.) at Barra and predominance of benthic diatoms during summer. Species of dinoflagellates and ciliates (mainly *Myrionecta rubra*) occurring during summer blooms at Barra were typically oceanic and seemed to have been transported inshore.

c) Diatom abundance and biomass were significantly correlated with chl *a*. There was a significant correlation between the seasonal patterns of chlorophyll and diatom abundance and biomass. Indeed, diatoms contributed an overall average of 53% of total phytoplankton biomass during LW and 35% of total biomass during LW with several conspicuous species (*Chaetoceros*, *Nitzchia* and *Pseudonitzchia* spp). This diatom predominance was confirmed by High Performance Liquid Chromatography (HPLC) analyses of photopigments during same time period (Pereira et al., 2007).

d) Large dinoflagellates were usually more conspicuous during HW at all 3 stations contributing an overall mean of 35% to total biomass during HW and only 16% during LW (mainly *Ceratium* and *Prorocentrum* spp.). Nanoflagellates (2-20 µm) were abundant and ubiquitous (mostly Cryptophytes) contributing an overall mean of 25% to total phytoplankton biomass regardless of tidal stage.

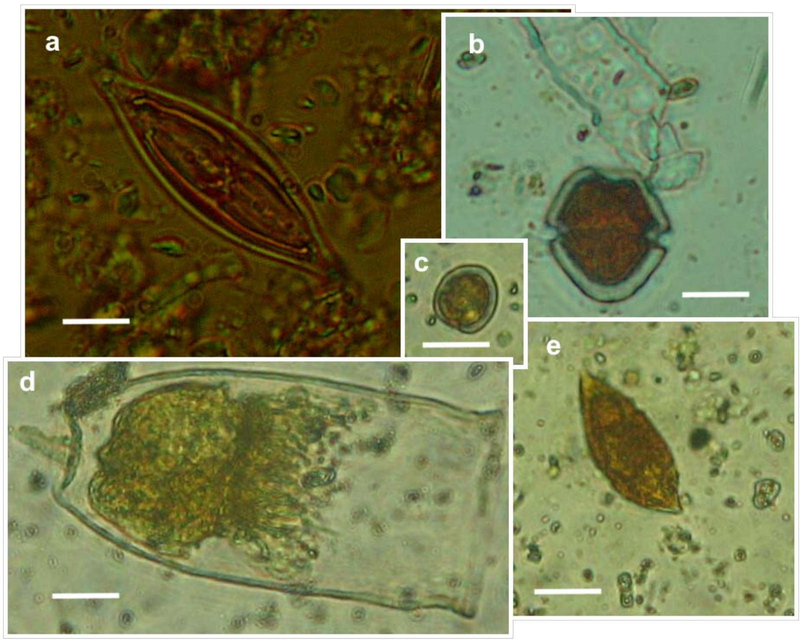

Figure 5.6.
Photomicrographs of larger microplankton species taken with lugol stained samples observed under phase-contrast inversion microscopy with 400X magnification. 5.6.a: pennate diatom *Navicula* sp.; 5.6.b : unidentified thecate dinoflagellate; 5.6.c: bloom-forming dinoflagellate *Prorocentrum minimum*; 5.6.d: large herbivorous tintinnid ciliate; 5.6.e: thecate dinoflagellate *Gyrodinium* sp. Courtesy of Rita B. Domingues. Bars: 20 µm

These trends were explained by the hydrodynamic regime of the Ria Formosa lagoon. Earlier observations confirmed that 80% of water exchange in the western lagoon occurred through the Faro-Olhão and Armona inlets (Silva et al., 2002). Newton and Icely (2002) stressed the important influence of the artificial inlet opened in June 1997 at Barra location (B in Fig. 5.2). In effect, floodwater from Barra inlet reduced water inflow of water from Ramalhete channel into the western Ancão basin, allowing rapid and substantial exchange of water between Barra and Ponte stations over a tidal cycle, but effectively reduced water exchange between Ramalhete and other stations. This circulation pattern in the Ancão Basin explained why patterns in phytoplankton community composition at Ramalhete in inner lagoon were strikingly different from those observed at Ponte and Barra in outer lagoon.
Photomicrographs of typical phytoplankton species are illustrated in Figure 5.5 and Figure 5.6. Figure 5.5 depicts typical pico- and nanophytoplankton taxa taken with epifluorescence microscopy stained with DAPI under UV or blue light, while Figure 5.6 photomicrographs of larger conspicuous species were taken using phase contrast inversion microscopy with Lugol staining (JGOFS Protocols 1994).

5.3. Quantification of main carbon fluxes in Ria Formosa

Phytoplankton primary production (PP) and bacterial production (BP) were determined following sampling strategy described in previous section using standard C14 incorporation methods. BP using ^{14}C-leucine incorporation followed method described in Chin-Leo and Kirchman (1988), whereas PP was determined by ^{14}C-bicarbonate fixation according to JGOFS standard protocols (1994). Figure 5.7 illustrates incubation set-up (5.7.a) for PP, filtration ramp for C14 incorporations (5.7.b) and bubbling method to purge unfixed CO_2 (5.7.c) in PP determinations.

Figure 5.7.
Equipment used in C14 methodology. 5.7.a: Primary Production (PP) incubation set-up; 5.7.b: filtration ramp used in C14 incorporations; 5.7.c: bubbling method used in PP. Courtesy of Pedro. A. Mendes.

Table 5.2 compiles means of bacterial abundance or Total Bacteria Number (TBN), Bacterial Biomass (BB), Phytoplankton Biomass (PB), Bacterial Production (PB) and phytoplankton Primary Production (PP). Bacteria growth is calculated by BP:BB and phytoplankton growth by PP:PB. Bacterial Carbon Demand was calculated by

BCD = BP / BGE whereby Bacterial Growth Efficiency (BGE)

BGE = (0,037+0,65 BP) / (1,8+BP)   according to del Giorgio and Cole (1998).

Table 5.2.

Microbial variable means at three stations for four sampling campaigns. TBN: Total Bacteria Number; BB: Bacteria Biomass; BP: Bacteria Production; BCD: Bacterial Carbon Demand; PB: chlorophyll-derived Phytoplankton Biomass; PP: Primary Production. Note ratios BP: BB = bacterial growth rates; PP:PB = phytoplankton growth rates. BCD:PP > 1: heterotrophy; BCD:PP < 1 autotrophy.

		June 2001			**September 2001**			**December 2001**			**April 2002**		
	Tide	**B**	**P**	**R**	**B**	**P**	**R**	**B**	**P**	**R**	**B**	**P**	**R**
TBN	HW	2.2	8.6	8.1	2.8	2.8	6.3	1.8	1.2	2.3	0.8	1.1	2.9
(10^9cells. L^{-1})	LW	6.9	1.2	7.7	4.4	5.8	9.4	2.1	3.8	2.9	3.5	5.4	4.2
BB	HW	24.3	98.2	86.1	29.2	31.9	86.6	22.9	12.7	24.2	8.3	11.5	35.5
(mgC. m^{-3})	LW	79.4	147.5	87.7	47.2	72.0	109.9	31.5	47.3	37.9	28.9	74.1	47.5
BP	HW	13.7	13.5	3.6	2.1	3.2	7.6	0.5	1.5	4.1	1.4	2.5	4.9
(µgC. L^{-1}. h^{-1})	LW	16.5	17.0	16.4	6.8	9.6	5.0	2.4	4.5	1.9	9.3	19.3	8.7
BCD	HW	23.8	23.4	8.1	5.9	7.5	14.4	3.1	4.9	9.0	4.8	6.4	10.3
(mgC. m^{-3}. h^{-1})	LW	28.0	28.9	28.0	13.1	17.5	10.3	6.3	9.5	5.4	17.0	32.3	16.1
BP:BB	HW	***0.56***	***0.14***	***0.04***	***0.07***	***0.10***	***0.09***	***0.02***	***0.12***	***0.17***	***0.17***	***0.22***	***0.14***
(h^{-1})	LW	***0.21***	***0.11***	***0.19***	***0.14***	***0.13***	***0.04***	***0.08***	***0.09***	***0.05***	***0.24***	***0.26***	***0.18***
PB	HW	92.9	83.6	154.2	61.6	46.7	96.3	11.4	11.7	13.8	10.8	14.8	13.7
(mgC. m^{-3})	LW	102.6	173.4	147.9	58.6	78.1	71.1	12.7	16.0	13.3	7.9	20.7	12.5
PP	HW	30.3	32.3	35.4	10.5	14.3	32.1	1.8	2.1	2.5	4.2	7.6	8.7
(µgC. L^{-1}. h^{-1})	LW	19.8	73.8	46.5	9.3	27.7	23.3	2.0	3.1	2.2	4.9	15.8	8.3
PP:PB	HW	***0.33***	***0.39***	***0.23***	***0.17***	***0.31***	***0.33***	***0.16***	***0.18***	***0.18***	***0.39***	***0.51***	***0.63***
(h^{-1})	LW	***0.19***	***0.43***	***0.31***	***0.16***	***0.35***	***0.33***	***0.16***	***0.19***	***0.16***	***0.62***	***0.76***	***0.66***
BCD:PP	HW	***0.79***	***0.72***	***0.10***	***0.23***	***0.56***	***0.53***	***0.45***	***1.72***	***2.33***	***3.60***	***1.14***	***0.84***
	LW	***1.41***	***0.39***	***0.35***	***0.60***	***1.41***	***0.63***	***0.44***	***3.15***	***3.06***	***2.45***	***3.47***	***2.04***

Total bacterial numbers (TBN), bacterial biomass (BB), bacterial production (BP), bacterial carbon demand (BCD) in Table 5.2 were consistently higher at LW throughout the year at Barra. A similar pattern occurred at Ponte except for a higher value of TBN at HW in June. However, in the case of Ramalhete, values were higher at HW, for TBN in June, for BP in September and December and for BCD in September and December. On the other hand, phytoplankton biomass (PB) and primary production (PP) were higher during HW at Barra in September and April, and at Ramalhete for all four seasons. PP had higher values for HW in June and September at Barra, and in September, December and April at Ramalhete. PB and PP values were consistently lower at HW compared to LW.

June and September 2001 values for bacterial production (BP) in the Ria were higher than most values reported for estuaries and salt marshes (Billen et al., 1990), whereas December and April values were consistent with other published values. All were within the range reported by Billen et al. (1990) for

estuarine environments, and consistent with values reported for Ria de Aveiro (Almeida et al., 2002). In June, BP and PP appeared to have inverse trends. However, statistical analyses showed no correlation between BP and either PP, pigments, TBN or BB. Furthermore, plotting Log BB vs. Log BP showed no C limitation of the bacterial community. According to the Billen et al., 1990 model, this indicated that bacteria were not controlled by bottom-up mechanisms, such as DOM availability.
In April 2002, an increase in bacteria and phytoplankton production was observed, although standing stocks remained similar to December 2001, resulting in a marked increase in specific production. BP was generally higher than PP, but there was no significant correlation between BP and PP. (Fig. 5.3). These observations suggested there was no coupling between PP and BP during spring. However, plotting Log BB vs. Log BP Billen et al. (1990), model application indicated that bacterial community was strongly limited by availability of dissolved organic carbon. Studies that show that bottom-up and top-down processes could change quickly within days and that the strength of bottom-up control could be influenced by changes in temperature (Vaqué et al., 2014). This is not surprising, since marine microorganisms in temperate regions survive near optimal temperature during summer and near null growth temperature during winter despite acclimatization and seasonal succession (Pomeroy and Wiebe, 2001).
Grazing (top-down control), substrate supply rates (bottom-up control) and temperature have been considered as main regulation factors of bacterial production (BP) in marine environments, whereas primary production (PP) is regulated by the combined effect of light, nutrients and temperature, as well as grazing (Vaqué et al., 2014). During summer, nutrients and organic matter input increased in the Ria Formosa due to a rise in tourist population. In fact, nutrient concentrations (data not shown) showed maxima in DIN (Dissolved Inorganic Nitrogen) and phosphates (P) in June 2001 with generally higher values observed at LW. Silicate (DSi) maximum values occurred in September 2001 (data not shown) with higher values at LW. This pattern of P and DSi variability indicated that sediments were main source of nutrients in the Ria Formosa. According to Justi et al. (1995) criteria for stoichiometric nutrient balance in coastal waters, there was a potential limitation in DIN, but not in P or DSi.
Phytoplankton exudation provides the main source of DOM for heterotrophic bacteria (see section 1). To assess to what extent Bacterial Carbon Demand (BCD) was satisfied by phytoplankton, an average of 20% of Primary Production was assumed to be lost to exudation. Then, Primary Production fulfilled at most 87.4 % of BCD in June 2001, 45.5 % in September 2001, 11.6 % in December 2001 and 17.5 % in April 2002. Therefore, the remainder dissolved carbon had to be supplied internally by protist "sloppy-feeding" (see section 5.1) or by external sources (land derived). Since grazing rates by phagotrophic protists were not available for this study, this additional source of carbon could not be assessed. However, recent studies in productive coastal waters, determined that 49% to 65% of Bacterial Production was grazed by protists (Vaqué et al., 2013), and a large fraction (>50%) of prey biomass is lost by "sloppy-feeding", thus this mechanism could largely supply remainder dissolved carbon necessary for BCD. So, the role of bacteria as land-derived DOM consumers could only be significant during cold seasons.
Furthermore, annual variations in BCD: PP (Table 5.2) indicated that the Ria underwent a marked shift from strongly autotrophic in June and September 2001 to heterotrophic in December 2001 and April 2002. A similar shift has also been reported for Ria de Aveiro (Almeida et al., 2002). This is explained, by the typical light limitation of phytoplankton in RF during winter, whereas during summer both light and temperature increase. Differences in phytoplankton community composition (see Fig. 5.3 and 5.4) could explain PP variations at HW and LW (Table 5.2) between Ramalhete and other stations. Furthermore, Newton and Mudge (2003) reported much lower water exchange rate at Ramalhete than at Barra and Ponte. Since Ramalhete is located at the main sewage treatment plant outlet for Faro (Fig. 5.2), this station is considerably more vulnerable to anthropogenic impact. When lagoon shifts from an autotrophic to heterotrophic regime during the cold season, this could enhance role of bacteria as DOM consumers and remineralizers, which is an important self-purification process in natural waters.

5.4. Assessment of trophic or ecological status of Ria Formosa

Previous Ria Formosa eutrophication reports concluded poor or pristine status depending on classification criteria, either nutrients only, or, in combination with chlorophyll and oxygen saturation (Newton et al., 2003). In contrast, criteria selected for eutrophication by the US National Estuarine Eutrophic Assessment based on symptoms, such as high chlorophyll *a* concentrations and low oxygen saturations, suggested that the lagoon was near pristine (Newton et al., 2003). To reconcile differences in assessing trophic status in Regions of Restricted Exchange (RRE), Tett et al. (2003) proposed measuring relative contribution of autotrophic and heterotrophic components of pico-nano and microplankton (size range: 0.2 to 200 μm) to pelagic production which can be estimated by comparing primary and bacterial production.

Annual Phytoplankton Primary Production (APPP) in RF (Table 5.3) was estimated to reach an overall mean of 533 g C. $m^{-2.}$ yr^{-1} at Barra, 317 g C. $m^{-2.}$ yr^{-1} at Ponte and 203 g C m^{-2} yr^{-1} at Ramalhete. APPP was calculated assuming a well mixed water column and that depth of euphotic layer was approximately 3 x Secchi depth (A. Barbosa, pers. comm.), so that the whole water column is euphotic in RF. APPP values were higher than overall mean of 252 g C .m^{-2}.yr^{-1} reported by Cloern et al. (2014) when reviewing data from 131 estuaries, which exhibited a large range from −105 (net pelagic production, Scheldt Estuary, Belgium) to 1890 g C. m^{-2}.yr^{-1} (Tamagawa Estuary, Japan). Following Scott Nixon's classification (Nixon, 1995), oligotrophic ecosystems possess APPP < 100 g C. m^{-2}. yr^{-1}, mesotrophic 100– 300 g C. m^{-2}.yr^{-1}, eutrophic 300–500 g C. m^{-2}. yr^{-1}, and hypertrophic APPP > 500 g C. m^{-2}. yr^{-1}. Thus, RF can be considered as eutrophic. However, since PP was determined only at the surface without any vertical profiles, APPP is only a rough estimate presuming mixed layer depth as euphotic layer (B: 10 m; P: 3 m; R: 2m).

Table 5.3.

Annual Phytoplankton Primary Production (APPP) and Annual Bacterial Production (ABP) at the three stations assuming mixed layer depth approx. equal to euphotic layer (Barra: 10 m; Ponte: 3 m; Ramalhete: 2 m)

	Barra	**Ponte**	**Ramalhete**
APPP (g C. m^{-2}. yr^{-1})	533	317	203
ABP (g C. m^{-2}. yr^{-1})	653	279	166

On the other hand, applying Carlson s (1977) Trophic State Index (TSI) developed for North American lakes, TSI based on chlorophyll was calculated to be 47.1 and based on Secchi depth 40.7. So, on a TSI scale of 0-100, RF could be classified as mesotrophic. However, considering Carlson s TSI general scheme, the range of chlorophyll values determined in RF (0.22 - 3.90 μg. L^{-1}) and overall mean of 1.18 μg. L^{-1}, RF would be classified closer to oligotrophic (0-2.6 μg. L^{-1}), rather than mesotrophic (2.6-20 μg. L^{-1}). Moreover, a trophic state index (TRIX) developed by Vollenweider (1998) and recommended by the European Environmental Agency (see Box 5.3) to monitor eutrophication in coastal waters (EEA report 7/2001), was calculated using overall mean chlorophyll (1.18), DIN (54.73), phosphates (42.11) in mg m^{-3} and 90th percentile oxygen saturation (130%) reported by Newton et al. (2003). This yielded a Trophic Score of 4.91 and a Trophic Index (TRIX) of 5.32, which falls within the lower range of TRIX values

Box 5.3. How is Trophic State Index (TRIX) recommended by European Environmental Agency calculated?

According to Vollenweider (1998), and as recommended in EEA report 7/2001
TROPHIC INDEX = (LOG [Ch*aD%O*N*P] -[-1.5])/1.2
Ch: chlorophyll *a* in mg. m-3
aD%O: absolute value of (% Oxygen - saturation)
N: Dissolved Inorganic Nitrogen concentration ($NH_4^+ + NO_3^- + NO_2^-$) in mg. m^{-3}
P: Dissolved Inorganic Phosphate (PO_4^{3-}) in mg. m-^{3}
Example:
Given following concentrations,
chl *a*: 22.3 mg. m^{-3}; % Oxygen saturation: 184%; N: 343 mg. m^{-3}; P: 5.0 mg. m^{-3}
Trophic Score = log(Ch*D%0*N*P) = **6.51**
Trophic Index = (6.51 + 1.51)/1.2 = **6.88**
Although Vollenweider (1998) developed this Index for Mediterranean waters, the EEA recommends its application for European NE Atlantic coastal waters using seasonal and regional means for limits. Thus, TRIX seasonal values vary from 4.9 and 7.1 in Danish waters (Kattegat) and from 7.5 to 9.0 in the North Sea (EEA 7/2001).

determined in Northern European coastal waters (EEA report7/2001) during 1998. Unfortunately, since there are no measurements of oxygen saturation in this study, no useful information could be derived from spatial and temporal variations. Towards the implementation of European Water Framework Directive (WFD 2000/60/EC) references and boundary conditions were determined in Portuguese Coastal and Transitional Waters as well as in Coastal Lagoons at selected reference sites. Boundary and reference values are generally expressed for the metric chl *a* 90th percentile (see Box 5.4). The High/Good boundary corresponds to a 50% deviation from the reference condition and the Good/Moderate boundary corresponds to a 50% from the High/Good boundary (see box 5.4). Brito et al. (2012) proposed an increase in chl *a* reference conditions of High/Good ecological status from 5.3 mg m^{-3} for Portuguese coastal lagoons (Coutinho et al., 2012) to 8 mg m^{-3} due to longer water residence times in inner

Box 5.4. What are existing Reference and Boundary Conditions in coastal and lagoon waters in Portugal

Following WFD recommendations, Reference and Boundary conditions should be established using all data available or at least during 6 months. Reference conditions depending on water typology should be established using 90% percentile as Reference condition and 50% deviation from this as High/Good Boundary and again 50% deviation from the latter as Good/Moderate boundary. The most commonly used Biological Quality Element is chlorophyll *a*, although other elements can be used such as total phytoplankton abundance and frequency of blooms above a certain threshold, also to be defined according to local phytoplankton community.
In Portugal, several coastal water typologies have been defined such as adjacent Coastal Waters (CWs) with strong or moderate upwelling and Coastal Lagoons (CW-Ls). According to Brito et al. (2012) and Coutinho et al. (2012) studying several coastal lagoons in southern (Ria Formosa, Ria de Alvor) and northern Portugal (Óbidos, Albufeira, St. André) reference and boundary conditions for chlorophyll *a* (mg. m-3) are as follows:

	Reference	High/Good	Good/Moderate
Coastal Waters	4.0	6.0	9.0
Southern Lagoons	5.3	8.0	12.0
Northern Lagoons*	6.7	10.0	15.0

(*open to ocean regime)

lagoon. Regardless of different proposed boundaries, the Ecological Status of RF as defined by the WFD could be considered as High .

In conclusion, the evaluation of trophic or ecological status in the RF lagoon using different indices and classification systems yielded ambiguous, if not contradictory results. Ideally, trophic status should be ascertained from microbial processes rather than standing stocks. Unfortunately, only "state" environmental variables such as nutrient and chlorophyll concentrations are routinely monitored. Rather than rendering judgement on a particular location or time period, it would be advisable to analyse longer time series of environmental variables. For the Ria Formosa lagoon, water quality indicators such as dissolved inorganic nutrients, transparency (Secchi depth) and chlorophyll could now be compiled for at least a 50-year period, albeit from different sources. Brito et al. (2012), as well as Barbosa (2010) reported decreasing long-term trends in chl. This decreasing trend in chlorophyll was attributed to increase bivalve filtering by Brito et al. (2012), while Barbosa (2010) analysing the 1967-2008 decadal period suggested that a global warming trend could be responsible.

Regrettably, scant information on oxygen saturation is available for the Ria. It is postulated here that a global warming trend could further deteriorate oxygen conditions with increasing water temperature and salinity. This could result in the development of hypoxia, particularly at night, which could drive denitrification processes and further decrease N budget as well as phytoplankton production in the lagoon. This potential oligotrophication trend should be addressed in future time series analyses.

Finally, there is increasing interest in using earth observations (EO) to monitor ecosystems by remote sensing. EO is a cost-effective tool to assess environmental systems at a synoptic scale with high spatial and temporal capacity on a global scale with ranges from years to decades. However, the use of EO for microbial populations and processes has been limited to relatively few studies. For example, Larsen et al. (2015) used remotely sensed environmental parameters to create a system-scale model of marine microbial metabolism for the Western English Channel. In Chapter 10, S. Cristina et al. discuss how the Sentinel satellites developed by the European Space Agency could be used for EO of the RF. These observations would enable future studies of the microbial population and processes of RF lagoon with increasing temporal resolution.

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References

Almeida, M.A., Cunha, M.A. & Alcântara, F., 2002. Seasonal change in the proportion of bacterial and phytoplankton production along a salinity gradient in a shallow estuary. *Hydrobiologia* 475/476: 251-262.

Azam, F., Fenchel, T., Field, J.G, Gray, J.S., Graf, L. A. Meyer-Reil, L.A. & Thingstad F., 1983. The ecological role of water-column microbes in the sea. *Marine Ecology - Progress Series* 10: 257-263.

Azam, F., 1998. Microbial control of oceanic carbon fluxes. *Science* 280: 694-696.

Barbosa, A. B., 2010. Seasonal and interannual variability of planktonic microbes in a mesotidal coastal lagoon (Ria Formosa, SE Portugal) - Impact of climatic changes and local human influences. In: Kennish, M.J., Paerl, H.W. (Eds.) Coastal Lagoons: Critical Habitats of Environmental Change. CRC Press, pp. 334–366.

Billen, G., Servais, P. & Becquevort, S., 1990. Dynamics of bacterioplankton in oligotrophic and eutrophic aquatic environments: bottom-up or top-down control? *Hydrobiologia* 207: 37-42.

Brito, A.C., Quental, T. , Coutinho, T.P., Branco, M.A., Falcão, M., Newton, A., Icely, J. & Moita,T., 2012. Phytoplankton dynamics in southern Portuguese coastal lagoons during a discontinuous period of 40 years: An overview. *Estuarine, Coastal and Shelf Science* 110: 147-156.

Carlson, R.E., 1977. A trophic state index for lakes. *Limnology & Oceanography* 22: 361-367.

Chin-Leo, G. & Kirchman, D., 1988. Estimating bacterial production in marine waters from the simultaneous incorporation of thymidine and leucine. *Applied Environmental Microbiology* 54: 1934-1939.

Cloern, J.E, Foster, S.Q. & Kleckner, A.E., 2014. Phytoplankton primary production in the world's estuarine-coastal ecosystems. *Biogeosciences* 11: 2477–2501.

Coutinho, M.T.P., Brito, A.C., Pereira, P., Gonçalves, A.S., Moita, M.T., 2012. A phytoplankton tool for water quality assessment in semi-enclosed coastal lagoons: Open vs closed regimes. *Estuarine, Coastal & Shelf Science* 110: 134-146.

del Giorgio, P.A. & Cole, J.J., 1998. Bacterial growth efficiency in natural aquatic systems. *Annual Revues of Ecology & Systematics* 29: 503-541.

Ducklow, h.W., Purdie, D.A., Williams, P.J. & Davies, J.M., 1986. Bacterioplankton: A Sink for Carbon in a Coastal Marine Plankton Community. *Science* 232: 865-867.

EEA, 2001. Eutrophication in Europe's coastal waters. European Environment Agency Topic Report nr. 7, 86 p.

Hillebrand, H., Duerselen, C.D., Kirschtel, D., Pollingher, U. & Zohary, T., 1999. Biovolume calculation for pelagic and benthic microalgae. *Journal of Phycology* 35: 403-424.

JGOFS, 1994. Protocols for the Joint Global Ocean Flux Study core measurements, I.O.C. Manual and Guides nr. 29, 170 p.

Justi , D., Rabalais, N.N., Turner, R.E. & Dortch, Q., 1995. Changes in nutrient structure of river dominated coastal waters: stoichiometric nutrient balance and its consequences. *Estuarine, Coastal & Shelf Science* 40: 339-356.

Larsen, P.E, Scott, N., Post, A.F., Field, D., Knight, R., Hamada Y. & Gilbert J.A., 2015. Satellite remote sensing data can be used to model marine microbial metabolite turnover. *The ISME Journal* 9: 166–179.

Newton, A. & Icely, J.D., 2002. Impact of Coastal Engineering on the Water Quality of the Ria Formosa Lagoon, Portugal. EURCOAST/EUCC Porto, Portugal. *The Changing Coast Littoral* 3: 417-421.

Newton, A., Icely, J.D., Falcão, M., Nobre, A., Nunes, J.P, Ferreira, J.G. & Vale, C., 2003. Evaluation of eutrophication in the Ria Formosa coastal lagoon, Portugal. *Continental Shelf Research* 23: 1945-1961.

Newton, A., & Mudge, S.M., 2003. Temperature and salinity regimes in a shallow, mesotidal lagoon, the Ria Formosa, Portugal. *Estuarine, Coastal & Shelf Science* 56: 1-13.

Newton. A., Icely, J.D., Cristina, S., Brito, A., Cardoso, A. C., Colijn, F., Riva, S.D., Gertz, F., Hansen, J.W., Holmer, M., Ivanova, K., Leppakoski, E., Canu, D.M., Mocenni, C., Mudge, S., Murray, N., Pejrup, M., Razinkovas, S., Reizopoulou, S., Pérez-Ruzafa, A., Schernewski, G., Schuber, H., Carr, L.C., Solidoro,C., Viaroli, P. & Zaldívar, J.M., 2014. An overview of ecological status, vulnerability and future perspectives of European large shallow, semi-enclosed coastal systems, lagoons and transitional waters. *Estuarine, Coastal & Shelf Science* 140: 95-122.

Nixon, S.W., 1995. Coastal marine eutrophication: a definition, social causes and future concerns. *Ophelia* 41: 199–219.

Norland, S., 1993. The relationship between biomass and volume of bacteria. In Kemp P.F., B.F.Sherr, E.B.Sherr & J.J.Cole (eds), Handbook of methods in aquatic microbial ecology. Lewis Publishers Boca Raton, U.S.A, pp. 303-307.

Pereira, M.G., Icely, J.D., Mudge, S.M., Newton, A. & Rodrigues, R., 2007. Temporal and spatial variation of phytoplankton pigments of the Ria Formosa lagoon, Southern Portugal. *Environmental Forensics* 8(3): 205-220.

Pomeroy, L.R. & Wiebe, W.J., 2001. Temperature and substrates as interactive limiting factors for marine heterotrophic bacteria. *Aquatic Microbial Ecology* 23:187-204.

Pomeroy, L.R., Williams, P.J., Azam, F. & Hobbie, J.E., 2007. The microbial loop. *Oceanography* 20(2): 28-33.

Silva, A., Leitão, J., Braunschweig, F. & Neves, R., 2002. Ria Formosa 3D hydrodynamic model. A contribution for the understanding of the Faro-Olhão inlet processes. EURCOAST/EUCC Porto, Portugal. *The Changing Coast Littoral* 2: 197-207.

Suttle, C.A., 2007. Marine viruses - major players in the global ecosystem. *Nature Reviews* 5: 801-812.

Tett, P., Gilpin, L., Svendsen, H., Erlandsson, C.P., Larsson, U., Kratzer, S., Fouilland, E., Janzen, C., Lee, J., Grenz, C., Newton, A., Ferreira, J.G., Fernandes, T., and Scory, S., 2003. Eutrophication and some european waters of restricted exchange. *Continental Shelf Research* 23: 1635-1671.

Tilstone, G.H., Figueiras, F.G, Fermí, E.G & Arbones, B., 1999. Significance of nano-phytoplankton photosynthesis and primary production in a coastal upwelling system (Ría de Vigo, NW Spain). *Marine Ecology Progress Series* 183: 13-27.

Vaqué, D., Alonso-Sáez, L., Arístegui, J., Agustí, S., Duarte, C.M., Montserrat Sala, M., Vasquez- Dominguez, E. & Gasol, J.M., 2014. Bacterial production and losses to predators along an open ocean productivity gradient in the Subtropical North East Atlantic Ocean. *Journal of Plankton Research* 36: 198–213.

Vollenweider, R.A., Giovanardi, F.M.G. & Rinaldi, A., 1998. Characterization of the trophic conditions of marine coastal waters with special reference to the NW Adriatic Sea: proposal for a trophic scale, turbidity and generalized water quality index. *Environmetrics* 9: 329-357.

WFD, 2000. Council Directive establishing a framework for Community action in the field of water policy (2000/60/EC), Official Journal of the European Communities, L327: 1-72.

6. Ecological dynamics of green macroalgae Ulvales in Ria Formosa: a tale of blooms and shapes

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6.1. Starting with a click...

The History of Science is the sum of the stories of men and women that produced it. They spent their lives gathering information, that once treated becomes knowledge and it is compiled in articles and books. Many stories in Science start with a bang, but this tale started with a humble click, back in 1988. In a cold winter morning, a very tall man stood alone in a windy road, near a Ria Formosa's mudflat taking photographs in low tide, apparently to nowhere. That same man, called Martin Sprung, repeated this monthly ritual, in the same spot, for the next years. Martin was a German zoologist, that came to the Algarve in the eighties to implement a German-Portuguese project to study the biology of Ria Formosa, which was very important in the development of the Marine Biology and Fisheries graduation course, in the recently created University of Algarve.

After two years of monthly photographs, a striking and unexpected pattern began to emerge: there was an intense bloom of green macroalgae mats (see Box 6.1) that started after the first Autumn rains, peaked during Winter and disappeared gradually during the following Spring, being almost non-existent during the Summer months (Sprung, 1994). These annual dynamics have been observed ever since, and their repetitive occurrences were studied in several surveys (Figure 6.1).

Box 6.1. Macroalgae bloom

Macroalgae is a name used for seaweeds and other benthic (attached to the bottom) marine algae that are visible to the naked eye. Macroalgae can be considered marine plants because they are photosynthetic organisms (produce sugar molecules using sunlight energy) and have similar ecological roles to other plants. However, macroalgae are distinct from other marine plants (e.g. seagrasses and mangroves) because they lack roots, leaves, flowers, and vascular tissues. Therefore, they normally live attached to hard surfaces (e.g. shells from dead animals, rocks or debris), and have quite complex life cycles and a wide variety of reproduction modes, that allow them to be considered opportunistic species. When environmental conditions are adequate to their development, macroalgae tend to growth very rapidly, covering wide intertidal surface areas. This phenomenon is called a macroalgae bloom (Lobban & Harrison, 1997; Barsanti & Gualtieri, 2006; Lee, 2008).

Traditionally, macroalgae are divided in three groups according to their colour and photosynthetic pigments: red, brown and green. This chapter focus only on some species of the green macroalgae.

Figure 6.1.
Macroalgae coverage in January (left) and September (right) 2001. The green macroalgae bloom had previously started in November 2000 and occurred again in October 2001 (Photographs by Jaime Aníbal, 2001).

Unfortunately, all the original photographs that were taken between 1988 and 1994 were lost after the tragic accident that took Martin Sprung's life in 2003. This chapter describes the research that was done thereafter in order to add lost pieces and try to solve the puzzle of the unusual annual pattern of Ria Formosa green macroalgae. As an Opera, this manuscript is also divided in three acts: the first will look over *What* is the green macroalgae annual dynamics in Ria Formosa; the second chapter will focus on *Where* are the algae blooms happening; and the third one will be dedicated to *Why* are all these phenomena occurring.

6.2. *What* is the green macroalgae annual dynamics in Ria Formosa?

In order to understand what are the issues related to this unusual green macroalgae winter bloom in the western area of Ria Formosa (along the Faro beach), several scientific studies were performed during a period of more than 20 years, from 1996 to 2018 (Figure 6.2).

In a study executed between February 1996 and February 1997, the macroalgae dynamics empirically observed in 1990 was for the first time quantitatively registered.

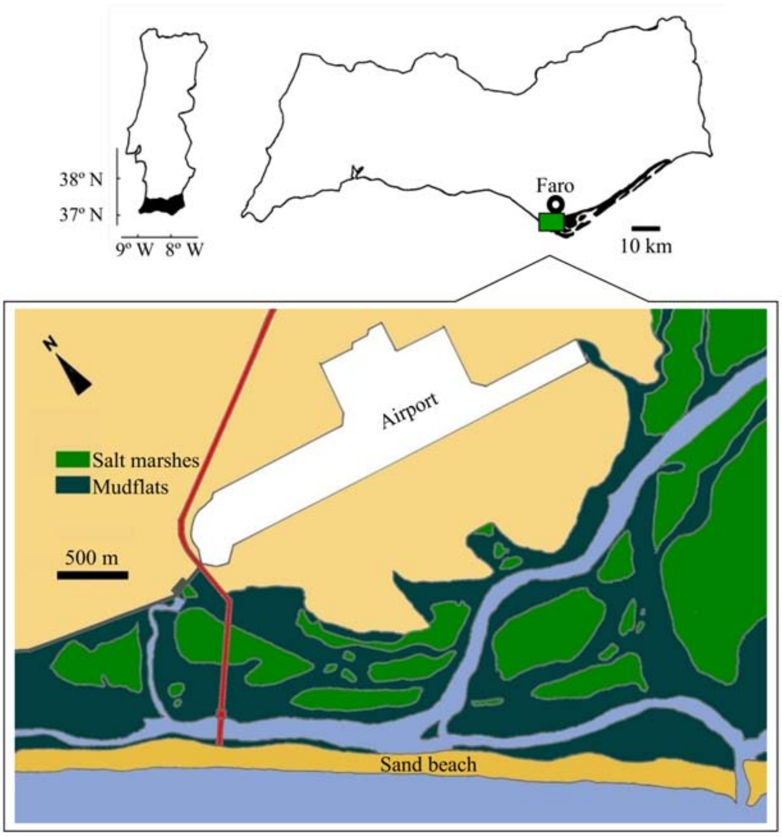

Figure 6.2.
Ria Formosa area adjacent to Faro beach.

The green macroalgae coverage peaked in the Winter months, decrease during Spring, almost disappeared in Summer, and bloomed again in Autumn (Figure 6.3).

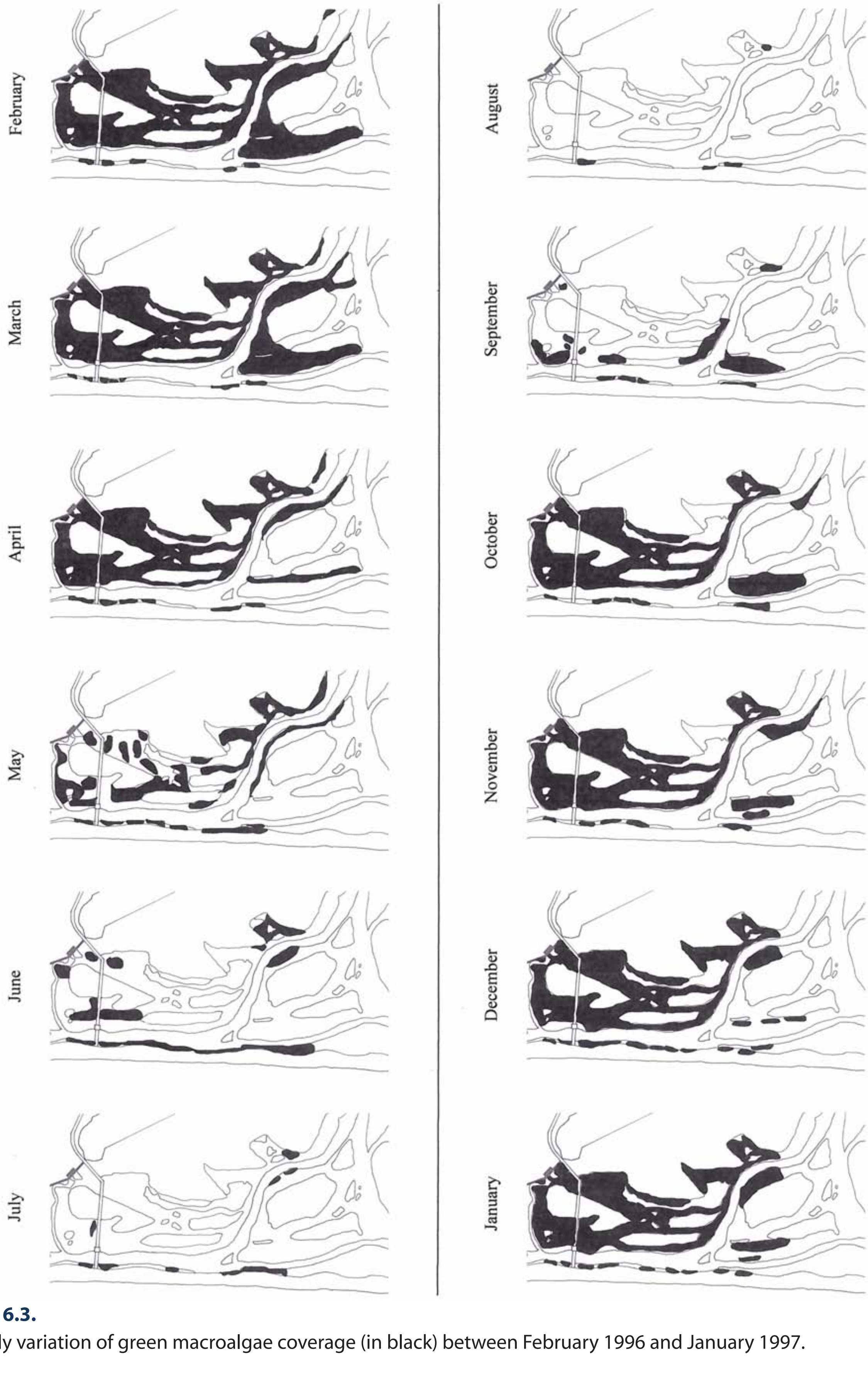

Figure 6.3.
Monthly variation of green macroalgae coverage (in black) between February 1996 and January 1997.

In the same study, the green macroalgae were identified as belonging to the order Ulvales, and to genera *Ulva* and *Enteromorpha*. Although morphologically distinct, both *taxa* coexisted in the same habitats. *Ulva* has a fan form appearance, and *Enteromorpha* presents a filamentous, hair-like, shape (Figure 6.4 and Box 6.2).

Figure 6.4.
Green macroalgae from the genera *Ulva* and *Enteromorpha* (Photographs by Jaime Aníbal, 2018).

The macroalgal biomass, measured as ash-free dry weight (AFDW), accompanied the sediments' coverage dynamics, with higher values in the Winter and Autumn months, and lower values in the end of Spring and beginning of Summer (Figure 6.5). After minima values of biomass during the Summer months, the new Ulvales bloom occurred in the end of September, after the first heavy rains of Autumn. Ulvales presented an annual average biomass of 25.9 g AFDW m^{-2}, with an annual production of 72,6 g m^{-2} y^{-1}. The annual average biomass of *Enteromorpha* (22.3 g AFDW m^{-2}) exhibited a clear dominance over *Ulva*'s (3.5 g AFDW m^{-2}), with annual production values of 74.6 g m^{-2} y^{-1} and 10.5 g m^{-2} y^{-1} respectively. Nevertheless, both genera followed the same dynamics of the Ulvales as a whole (Aníbal, 1998).

Box 6.2. Are *Ulva* and *Enteromorpha* distinct genera?

Although some phylogenetic research has been providing indications that *Ulva* and *Enteromorpha* are not distinct evolutionary entities and should not be considered as separate genera (Hayden et al., 2003), the morphological differences between species of the genus *Ulva* and species of the genus *Enteromorpha* can be responsible for distinct adaptive strategies to stress factors such as current induced shear stress. These differences might be important as to whether the species settle on more exposed convex areas or in more sheltered concave zones of the tidal flats. Therefore, in this chapter, the two *taxa* will be presented as separate genera.

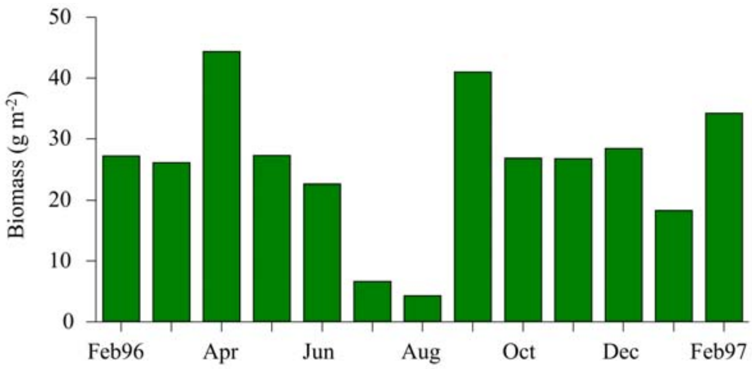

Figure 6.5.
Monthly variation of Ulvales biomass between February 1996 and February 1997.

In another field study done between 1999 and 2001 (Aníbal, 2004), the same Ulvales dynamics was observed (Figure 6.6 and Box 6.3).

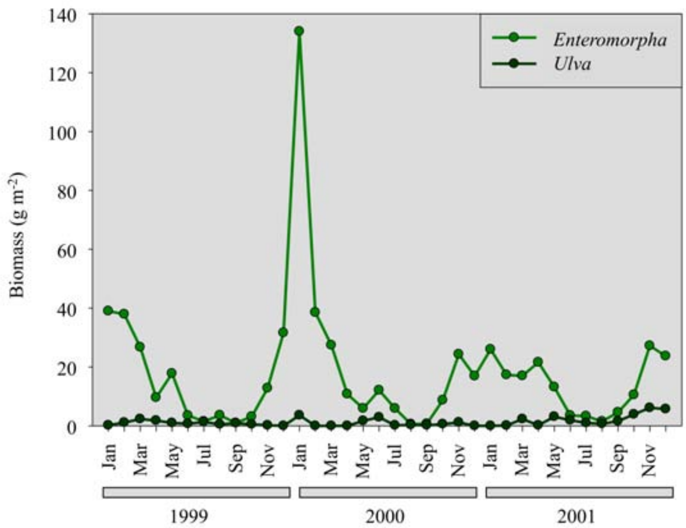

Figure 6.6.
Monthly variation of *Enteromorpha* and *Ulva* biomass between January 1999 and December 2001.

Box 6.3. Economic impact of macroalgae production in the world

According to the annual report on the state of the world fisheries and aquaculture of the Food and Agriculture Organization of the United Nations (FAO, 2018), aquaculture was the source of 96.5 percent by volume of the total 31.2 million tonnes of wild-collected and cultivated aquatic plants combined. Global production of farmed aquatic plants, overwhelmingly dominated by seaweeds (also known as macroalgae), grew in output volume from 13.5 million tonnes in 1995 to 30.1 million tonnes in 2016, with the first-sale value estimated at USD 11.7 billion.

Seaweeds and other algae are used as food (traditionally in China, Japan and the Republic of Korea), in animal feed, fertilizers, pharmaceuticals and cosmetics and for other purposes. Seaweeds are industrially processed to extract thickening agents such as alginate, agar and carrageenan or used, generally in dried powder form, as an animal feed additive. Increasing attention is also focusing on the nutritional value of several seaweed species, because of their high content of vitamins (particularly A, C and B-12), minerals (e.g. iron, calcium, iodine, potassium, selenium) and plant-based protein. Seaweed is also one of the only non-fish sources of natural omega-3 long-chain fatty acids. Several cosmetics have been commercialized from the seaweeds. Research is also exploring the use of seaweed as a salt substitute and in the industrial preparation of biofuel.

For more information about these issues consult http://www.fao.org/home/en/

6.3. *Where* are the green macroalgae blooms happening?

When using a bird's eye view to observe the muds and sands adjacent to Faro beach, they all seem flat plains, although a closer look reveals another geomorphologic reality. The flat plains are a succession of concave and convex section, especially in the mudflats (Figure 6.7).

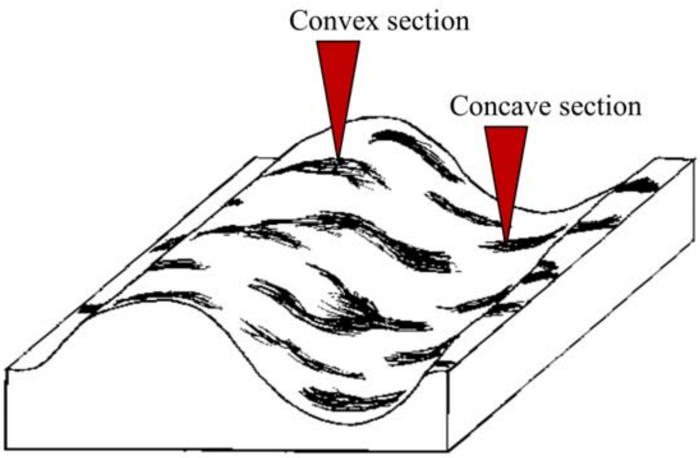

Figure 6.7.
Tidal flats' convex and concave sections.

A survey done in the study area in 2001 showed a clear distinction between convex and concave sections regarding sedimentological parameters (Aníbal et al., 2007). The concave sections presented a higher percentage of silt sediments, water content and organic matter. On the other hand, the convex sections had a higher composition in clay sediments. These results supported all the experimental design of the studies implemented to solve the following "*Why*…" question.

6.4. *Why* are all these phenomena occurring?

Once this green macroalgae phenomenon was characterized, the foundations for more detailed and specific research studies were created.

Photosynthetic organisms, such as green macroalgae live in the surface of sediments. Their lifecycle and dynamics can be constrained by two types of controls (Figure 6.8 and Box 6.4): "top-down control" done by herbivores, versus "bottom-up control" performed by nutrients availability and other abiotic factors (Valiela, 1995; Lynam et al., 2017).

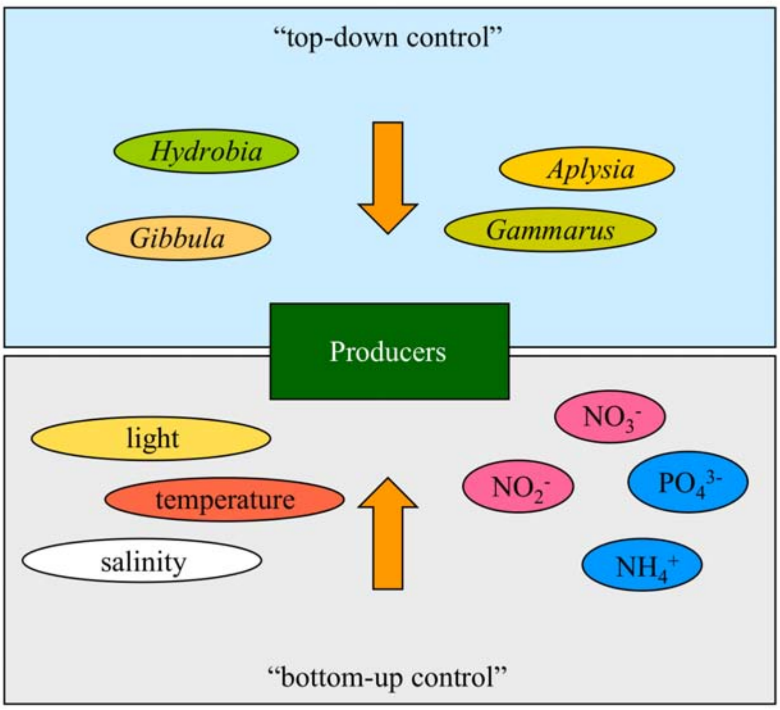

Figure 6.8.
"top-down control" versus "bottom-up control".

Box 6.4. Top-down control & bottom-up control

In an ecosystem, there are two types of controls on a population: bottom-up control, which is the limitation placed by resources allowing growth such as food source, habitat, or space, and top-down control, which is the limitation placed by factors controlling death such as predation, disease, or natural disasters.
In a world of limitless food resources, a population should be able to reproduce and expand their population exponentially. But in the real word, there will be years with abundant food resources, and years with scarcity. Thus, food resources can set the maximum limit of a population at any given time (bottom-up control).
Conversely, when the population gets too large, the predators drive it back down (top-down control). But the resulting decrease in their prey reduces the predator population, by reducing their food supply, allowing the prey to bounce back. Consequently, the bottom-up and top-down controls tend to regulate the stability of a population in an ecosystem. The bottom-up resources set the limit for the maximum healthy population, and the top-down forces kill off individuals from a large population, preventing overexploitation. The idea that populations interact and regulate one another is the fundamentals for wildlife conservation policies.

Because Martin Sprung was a Zoologist, the obvious starting hypothesis focused on the potential herbivory (top-down control) performed on the green macroalgae by the macroepifauna (Box 6.5).
The study of the potential top-down control done by the macroepifauna on the Ulvales was based on the following hypothesis: normally the animals' lifecycle is related to the seasons; the animals species begin to increase in numbers during the Spring, peaks their abundance and biomass during the Summer and start to decrease during Autumn; if these animals feed on the macroalgae, the only period of the year when the macroalgae can bloom is during the Winter period, because it corresponds to the macroepifauna minima for abundance and biomass.

Box 6.5. Macroepifauna

Organisms that are visible to the naked eye, bigger than 0.5 mm (macro), living at the sediment surface (epi) and belonging to the animal kingdom (fauna). The animals may originate from very diverse taxonomic groups, such as gastropods, crustaceans, insects, echinoderms or fishes.

The aim of the herbivory study was to access the impact of the herbivory performed by the macroepifauna over the green macroalgae present in the intertidal zones in the western area of Ria Formosa. The annual survey made in 1996-1997 allowed to identify and quantify, besides Ulvales' genera, 44 *taxa* of macroepifauna (Table 6.1).

In the mudflats, there was a clear distinction between the convex and the concave sections (Figure 6.9). The convex sections were characterized by higher Ulvales biomass, but fewer macroepifauna species and lower faunistic biomass, with a clear dominance in abundance of *Hydrobia ulvae* (Mesogastropoda). Concave sections of the sediment presented lower Ulvales biomass, but a more diverse macroepifauna, dominated by the higher biomass of *Gibbula umbilicalis* (Archaeogastropoda), *Cerithium vulgatum* (Mesogastropoda), *Nassarius pfeifferi* (Neogastropoda), *Haminaea navicular* (Cephalaspidea), *Melita palmata* (Amphipoda) and *Carcinus maenas* (Decapoda).

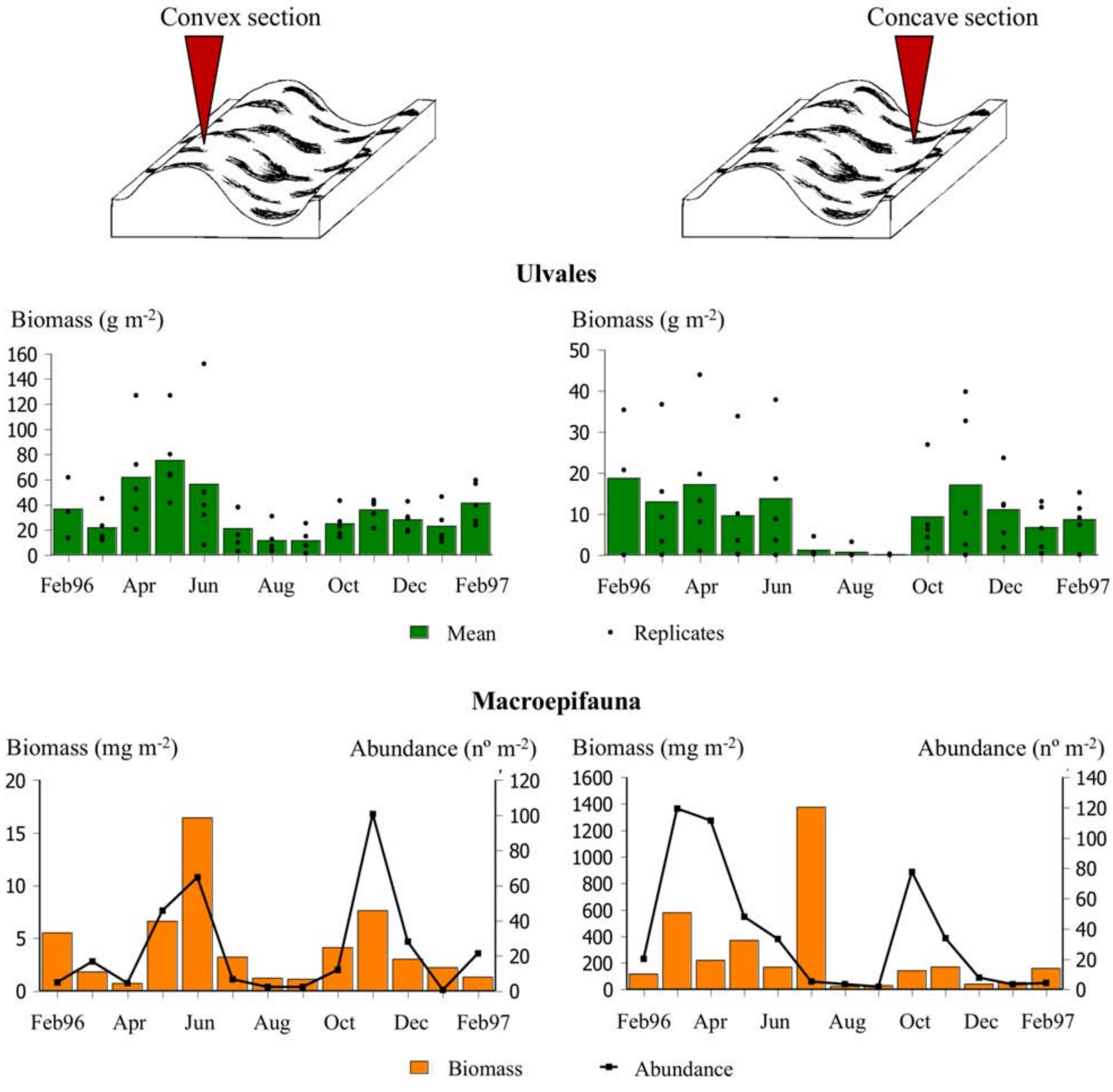

Figure 6.9.
Comparison of the green macroalgae and the macroepifauna dynamics between convex and concave sections of the sediment.

Table 6.1.
Macroepifauna identified during the field survey dedicated to the impact of herbivory over the green macroalgae. Abundance (n.º individuals m^{-2}) and biomass (mg AFDW m^{-2}) are average values for the western region of Ria Formosa.

Phylum	Class	Species	Abundance (nº m^{-2})	Biomass (mg m^{-2})
Cnidaria	Anthozoa	*Actinia equina*	0.02	1.22
		Anemonia sulcata	0.48	10.08
Mollusca	Amphineura	*Acanthochiton crinita*	0.03	0.60
		Chiton olivaceus	0.15	0.31
	Gastropoda	*Monodonta lineata*	0.92	83.48
		Gibbula umbilicalis	9.30	297.31
		Gibbula varia	2.28	158.15
		Gibbula pennanti	0.14	5.80
		Hydrobia ulvae	536.53	76.48
		Hydrobia ventrosa	8.22	0.67
		Rissoa membranacea	0.19	0.54
		Cerithium vulgatum	0.43	66.02
		Bittium reticulatum	1.43	1.97
		Calyptraea chinensis	0.01	0.03
		Ocenebra erinacea	0.01	1.68
		Ocinebrina aciculata	0.10	0.13
		Columbella rustica	0.01	0.93
		Amyclina cornicula	1.00	23.62
		Nassarius pfeifferi	9.34	236.93
		Haminaea navicula	8.64	104.53
		Aplysia depilans	0.02	11.47
		Aplysia fasciata	0.11	345.27
Arthropoda	Crustacea	*Balanus perforatus*	0.02	0.13
		Nebalia sp.	0.46	0.16
		Tanais dulongii	36.85	8.75
		Cyathura carinata	13.38	8.24
		Sphaeroma spp.	0.31	0.54
		Idotea chelipes	0.64	0.88
		Gammarus sp.	3.39	2.67
		Melita palmata	135.45	35.28
		Elasmopus rapaz	0.07	0.03
		Microdeutopus sp.	5.19	0.98
		Palaemon elegans	0.55	9.35
		Palaemonetes varians	0.17	6.06
		Crangon crangon	0.01	0.05
		Upogebia pusilla	0.03	3.08
		Carcinus maenas	3.60	728.23
		Pachygrapsus marmoratus	0.36	179.15
	Insecta	Chiromidae (larvae)	4.44	0.41
		Tipulidae (larvae)	7.67	6.84
Echinodermata	Holothurioidea	*Holothuria* sp.	0.09	0.41
	Ophiuroidea	*Amphipholis* sp.	0.01	0.03
Vertebrata	Osteichthyes	*Anguilla anguilla*	0.21	5.13
		Pomatoschistus minutus	0.17	7.90

An interesting fact was that the dynamics of the macroalgae and the macroepifauna were not complementary, as expected in our original hypothesis, but almost concordant in peak seasonality, and biomass and abundance dynamics. Almost all macroepifauna species had similar trends to those of the Ulvales, but for different reasons. From the species that are associated to the algae, almost all of them are detritivorous, possibly because the algae detritus is more easily assimilated by the individual gastric system, since it is already conditioned by microorganisms. There were some species that feed on the epiphytes on the algae (e.g. *Hydrobia*) and others just sought for refuge from its predators (e.g. juvenile fishes) or adverse abiotic conditions (Valiela, 1995; Schories et al., 2000).
To confirm these evidences, an herbivory laboratory study was done in 1999. The top potential herbivores (the previous mentioned seven species that dominated the macroepifauna) were chosen between the 44 identified species, taking into account their high values of biomass or abundance. Interestingly, none of these species exhibited a significant consumption of green macroalgae.
In conclusion, the intertidal areas of Ria Formosa are systems with low Ulvales herbivory, meaning that they are not top-down controlled. As other similar systems in the World, like the Mondego Estuary (Martins & Marques, 2002) or the Lagoon of Venice (Sfriso, 1995), the green macroalgae primary production is controlled by nutrients availability and favourable climatic conditions, which correspond to the bottom-up control paradigm (Valiela et al., 1997).
Between 1999 and 2001, another survey done in the same Ria Formosa area (Aníbal, 2004) allowed to assess which abiotic factors were dominant in controlling the Ulvales dynamics (bottom-up control). This study focused on the effects of the following abiotic factors on the Ulvales dynamics: temperature (water, sediment and air), rainfall, solar radiation, sediment characteristics (organic matter, water content and porosity) and pore water nutrients (nitrates, ammonia and phosphates).
After gathering and analysing all field and laboratory data, the Ulvales dynamics seemed to be controlled by two key moments: 1) the bloom beginning and 2) the bloom decay. The starting point of the Ulvales bloom appears to be originated by the conjunction of temperature decrease, photoperiod reduction, heavy rainfalls and high nutrient reserve concentrations in the sediment. On the other hand, the bloom decay seems to be related to temperature increase (leads to desiccation), photoperiod and solar radiation increase (provokes photoinhibition) and air relative humidity decrease (aggravates desiccation). It is important to note that phosphorus was the limiting element when compared with nitrogen, making sediment's pore water phosphate concentration a paramount nutrient resource for the primary producers (Schlesinger, 1997). Another striking observation was the fact that nitrates seemed to have higher concentrations in the deeper sediments layers, which might indicate the presence of submarine groundwater discharges (Rocha et al., 2016).
In this type of intertidal environment, macroalgae are not the only photosynthetic organisms with opportunistic life strategies. Along with Ulvales, microphytobenthos (Box 6.6) are competing for the same abiotic and nutrient resources (Figure 6.10).

Box 6.6. Microphytobenthos

Organisms smaller than 0.5 mm (micro), that are photosynthetic (phyto) and live in the sediment (benthos). In this work, chlorophyll a determinations were used as a proxy for microphytobenthos quantification. The taxonomic composition of microphytobenthos was mainly constituted by diatoms from the genera *Navicula*, *Pleurosigma* and *Tabellaria*.

The two previous mentioned key moments in the annual Ulvales dynamics may happen in two phases: 1) high primary production, from October to May, where nutrient competition between macroalgae and microphytobenthos controls the nutrient availability to Ulvales and 2) low primary production, from May to September, where photoinhibition, desiccation, organic matter increase and higher remineralisation impairs the development of photosynthetic organisms.

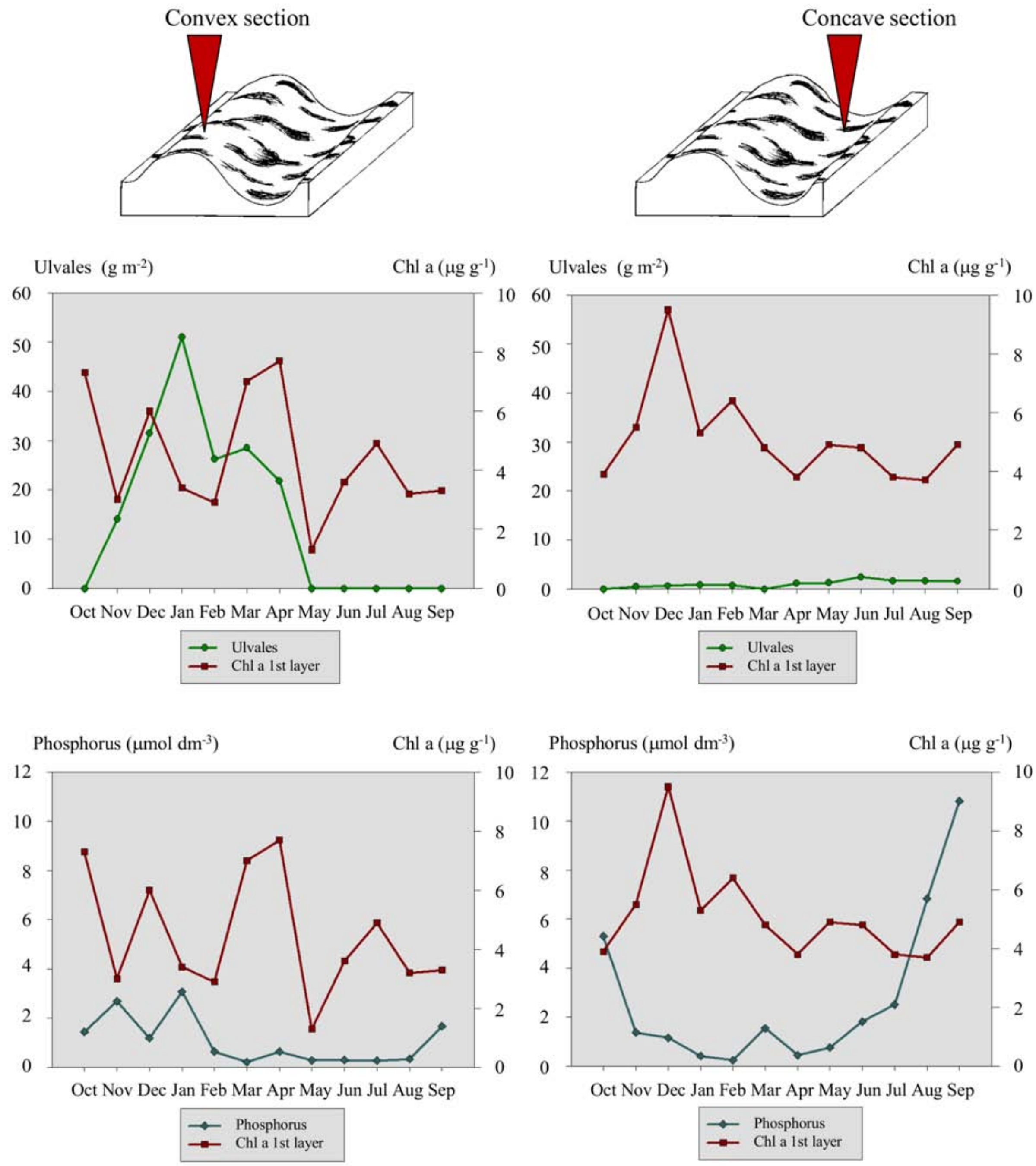

Figure 6.10.
Monthly dynamics of Ulvales biomass, chlorophyll a content in the first layer (1 cm) of sediment and phosphorus concentration in convex and concave sections of the sediments.

In Ria Formosa, the main source of nutrients for the benthonic primary producers is sedimentary remineralization, meaning that nutrients come from below and not from the water above. Since microphytobenthos lives in the first millimetres of the sediment, they are in a position that allows them to be able to uptake nutrients prior to other photosynthetic organisms (e.g. macroalgae), that only live in the sediment surface.

From the two previous described surveys, a conceptual diagram arose, linking the green macroalgae dynamics with the microphytobenthos competition and the nutrients availability (Figure 6.11).

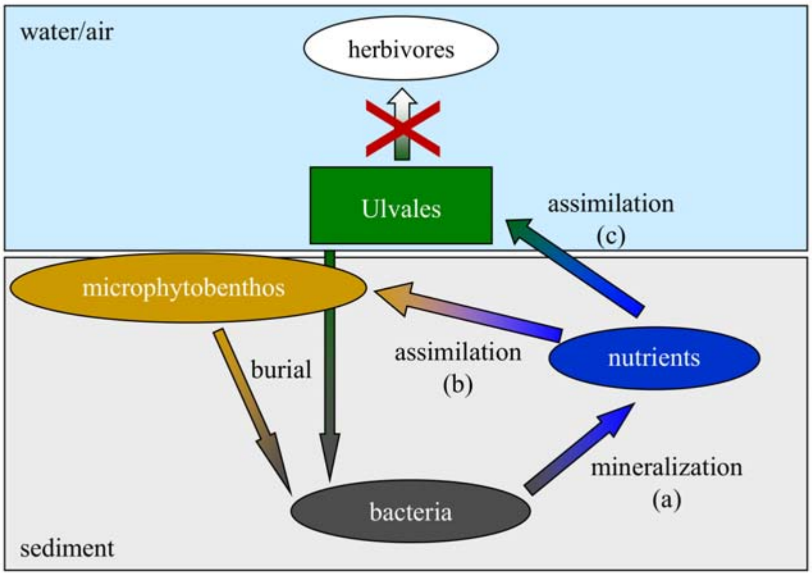

Figure 6.11.
Conceptual diagram of the forcing factors controlling the Ulvales dynamics in Ria Formosa.

From the conclusions of the field survey done in 1996-1997, it was possible to withdraw the herbivory as a significant forcing function in the Ulvales dynamics. The 1999-2001 survey allowed to acknowledge that when the increase in bacterial mineralization ($a > 0$) leads to a swift nutrients assimilation by diatoms ($b > 0$), creating conditions to a microphytobenthos bloom ($b = a$), the Ulvales are hindered to assimilate nutrients ($c = 0$) and increase their biomass. As the microphytobenthos increases, it also increases its demand for nutrients, until the point where they will begin to decrease ($b > a$), leading to the microphytobenthos collapse and posterior burial. This new source of organic matter to be remineralized will rapidly increase the nutrients pools in the sediment ($a > b$), creating conditions for the assimilation by the Ulvales ($c > 0$) and consequent green macroalgae bloom.
This conceptual diagram allowed to create a dynamic model using STELLA visual programming language (Figure 6.12), where the Ulvales biomass dynamics was simulated based on its intrinsic characteristics, temperature, light, nutrients and meteorological data (Jørgensen & Bendoricchio, 2001).

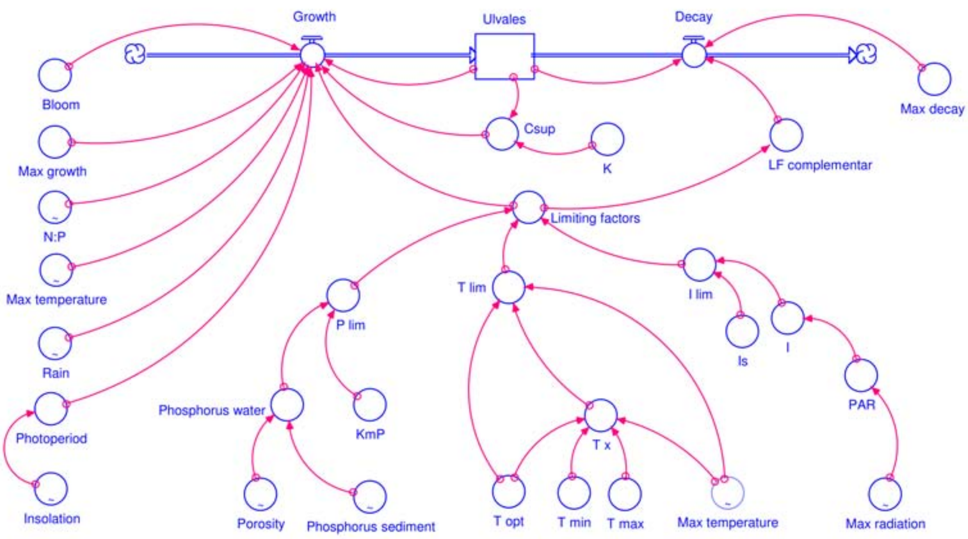

Figure 6.12.
Dynamic model of Ulvales using STELLA visual programming language.

The biomass results obtained from the model were compared with the observed values using statistical methods, that allowed to attain the following outcomes:
Model II regression
Simulated biomass = 0.586 Observed biomass – 1.075; $p < 0.005$; $n = 11$; $r^2 = 0.604$
Spearman correlation
$r = 0.863$; $p < 0.001$; $n = 11$
In conclusion, the model's output produced a simulation of the Ulvales's biomass dynamics that could explain more than 60% of the observed biomass variation (Figure 6.13).

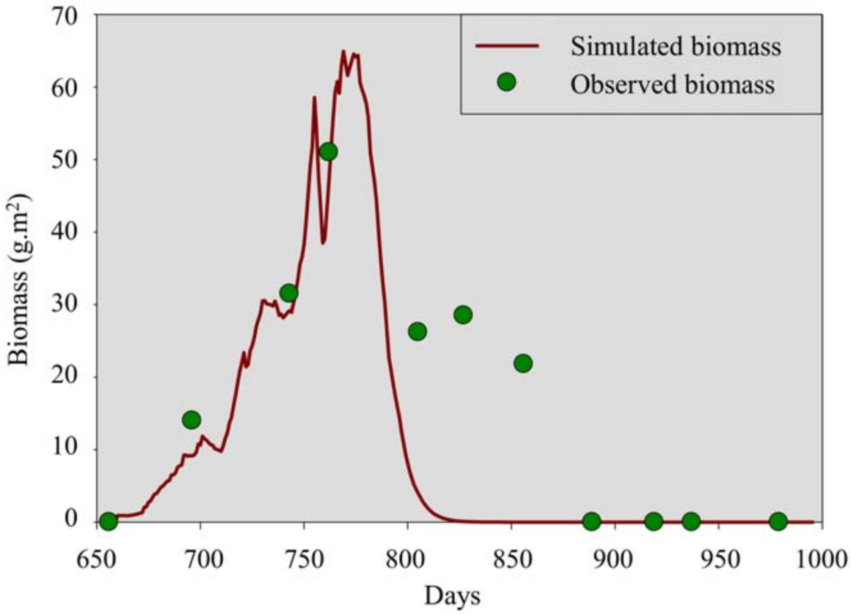

Figure 6.13.
Comparison between the Ulvales observed biomass and the simulated values obtained though the STELLA model output.

Ecological systems are very complex, and include many external variables. In this case, it can be considered that the 60.4% adjustment corresponds to the variables temperature, solar radiation and phosphorus concentration; the remaining 39.6% would explain the effect distributed by many other system variables, which were not considered in the model.

6.5. Ending with a click…

This tale of blooms and shapes started with a click and should also end with a click. In order to achieve this objective, monthly photographs were taken from December 2016 to June 2018, near the bridge that allows access to the Faro beach (Figure 6.14).

Figure 6.14.
Green macroalgae sediments coverage from December 2016 to June 2018. Photos were taken in the west (left) and east (right) sides of the road leading to Faro beach bridge (Photographs by Jaime Aníbal, 2018).

As expected, the Ulvales dynamics followed a very pronounced seasonal variation, with Winter blooms and Summer months without any macroalgal biomass. Once again, the beginning of Ulvales blooms followed the first Autumn or Winter heavy rains. This issue was especially evident in the last green macroalgae bloom. The Autumn of 2017 was particularly dry and the first rains only occurred during the month of January 2018; a couple of weeks following this phenomenon, the Ulvales bloom materialised. In the following March, the rainfalls were very heavy, and a week later the bloom was further increased.
The visual observation of the Ulvales dynamics shown in the photographs clearly indicates that the green macroalgae dynamics observed for the first time in 1988, still happens presently, and probably will continue to happen in the future.
With a starting click, an interesting puzzle was unexpectedly revealed, and with a finishing click, a few more pieces were added to an almost solved puzzle. Usually in science, the questions that arise after a concluded work are always more numerous than those that have been objectively answered. Notwithstanding, this chapter might be the basis for a series of future work, which could unveil explanations to the questions that were still unanswered.

Acknowledgements

I would like to thank Martin Sprung and Carlos Rocha for their truly inspiring supervision during my MSc and PhD thesis, without whom I would have never reach the end of the tunnel.
Unfortunately, Martin Sprung left us before he could see the conclusion of the field work and all the interesting hypothesis raised by the results. To him, I dedicate this chapter!

References

Aníbal, J., 1998. Impacte da macroepifauna sobre as macroalgas Ulvales (Chlorophyta) na Ria Formosa. Dissertação de Mestrado em Ecologia. Universidade de Coimbra, Coimbra, 73 p.

Aníbal, J., 2004. Processos ecológicos que controlam a dinâmica das macroalgas Ulvales (Chlorophyta) na Ria Formosa. Tese de Doutoramento em Ecologia. Universidade do Algarve, Faro, 151 p.

Aníbal, J., Rocha, C. & Sprung, M., 2007. Mudflat surface morphology as a structuring agent of algae and associated macroepifauna communities: a case study in Ria Formosa. *Journal of Sea Research* 57: 36-46.

Barsanti, L., Gualtieri, P., 2006. Algae: anatomy, biochemistry, and biotechnology. Taylor & Francis Group, LLC, Boca Ranton, 301 p.

FAO, 2018. The State of World Fisheries and Aquaculture 2018 - Meeting the sustainable development goals. Food and Agriculture Organization of the United Nations, Rome, 210 p.

Hayden, H.S., Blomster, J., Maggs, C.A., Silva, P.C., Stanhope, M.J. & Waaland, J.R., 2003. Linnaeus was right all along: Ulva and Enteromorpha are not distinct genera. *European Journal of Phycology* 38: 277-294.

Jørgensen, S.E. & Bendoricchio, G., 2001. Fundamentals of ecological modelling. Elsevier, Amsterdam, 530 p.

Lee, R.E., 2008. Phycology. Cambridge University Press, Cambridge, 547 p.

Lobban, C. & Harrison, P., 1997. Seaweed ecology and physiology. Cambridge University Press, Cambridge, 366 p.

Lynam, C.P., Llope, M., Möllmann, C., Helaouët, P., Bayliss-Brown, G.A. & Stenseth, N.C., 2017. Interaction between top-down and bottom-up control in marine food webs. *PNAS* 114: 1952-1957.

Martins, I. & Marques, J.C., 2002. A model for the growth of opportunistic macroalgae (Enteromorpha sp.) in tidal estuaries. *Estuarine, Coastal and Shelf Science* 55: 247-257.

Rocha, C., Veiga-Pires, C., Scholten, J., Knoeller, K., Gröcke, D.R., Carvalho, L., Aníbal, J. & Wilson, J., 2016.

Assessing land-ocean connectivity via submarine groundwater discharge (SGD) in the Ria Formosa Lagoon (Portugal): combining radon measurements and stable isotope hydrology. *Hydrology and Earth System Sciences* 20: 3077-3098.

Schories, D., Aníbal, J., Chapman, A.S., Herre, E., Isaksson, I., Lillebo, A.I., Pihl, L., Reise, K., Sprung, M. & Thiel, M., 2000. Flagging greens: hydrobiid snails as substrata for the development of green algal mats (Enteromorpha spp.) on tidal flats of North Atlantic coasts. *Marine Ecology Progress Series* 199: 127-136.

Schlesinger, W.H., 1997. Biogeochemistry: an analysis of global change. Academic Press, San Diego, 588 p.

Sfriso, A., 1995. Temporal and spatial responses of growth of Ulva rigida C. Ag. to environmental and tissue concentration of nutrients in the lagoon of Venice. *Botanica Marina* 38: 557-573.

Sprung, P., 1994. Macrobenthic secondary production in the intertidal zone of Ria Formosa - a lagoon in southern Portugal. *Estuarine, Coastal and Shelf Science* 38: 539-558.

Valiela, I., 1995. Marine ecological processes. Springer-Verlag, New York, 686 p.

Valiela, I., McClelland, J., Hauxwell, J., Behr, P. J., Hersh, D. & Foreman, K., 1997. Macroalgal blooms in shallow estuaries: controls and ecophysiological and ecosystem consequences. *Limnology and Oceanography* 42: 1105-1118.

7. Metal contamination in Ria Formosa saltmarsh sediments and halophyte vegetation

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Coastal saltmarshes may be defined as areas bordering saline water bodies vegetated by vascular plants (Box 7.1) such as herbs, grasses or low shrubs (Adam, 1990).

Saltmarsh vegetation may retain certain substances from anthropogenic activities in surrounding areas, providing a control of contaminants such as heavy metals, coming from industry, agriculture and urbanization. In the last decades there are been an increase in urbanization and industrialization of the area surrounding *Marim – Ria Formosa*, where this study was performed (Figure 7.1), focused on the metal contents in sediments and in its distribution among *Spartina maritima* and *Sarcocornia fruticosa* organs.

Box 7.1. What is halophyte vegetation?

Saltmarsh vascular plants are denominated halophyte vegetation due to the resistant to the high levels of salt to which are subject.

Figure 7.1.
Location of study area, *Marim – Ria Formosa*.

7.1. Metals - contamination and toxicity

Soil contamination by metals differs from air or water pollution, because trace metals persist in soil much longer than in other compartments of biosphere (Padmavathiamma and Li, 2007) moreover metals tend to be retained more strongly in wetland soils compared with upland soils (Gambrell, 1994). Trace metals rapidly sorb to particulate matter and accumulate in fine-grained sediments of saltmarsh environments, and persist for long periods of time in benthic habitats. Therefore, sediments represent a major repository for trace metals which may be later remobilized to the water column, the concentrations of trace metals are three to five orders of magnitude greater in the bottom sediments of estuaries than in overlying waters (Kennish, 2001).

Anthropogenic inputs substantially augment natural loads and, in some industrialized and urbanized coastal systems, can exceed natural concentrations by orders of magnitude. Included here are such diverse sources as municipal and industrial wastewater discharges, leaching of antifouling paints, dredged material disposal, combustion of fossil fuels, mining of metal ores, smelting operations, refining, electroplating and the manufacture of dyes, paints and textiles. Periodical tidal flooding of saltmarshes provides large quantities of these pollutants to the marsh ecosystem (Reboreda & Caçador, 2007). Biological and geochemical processes as well as tidal cycles control the distribution and behaviour of trace metals.

Trace metals pose a significant threat to organisms because above threshold availability, act as enzyme inhibitors. Biota exposed to elevated trace metal concentrations often experience serious physiological, reproductive and development changes (Kennish, 2001).

7.2. Sediments and halophyte vegetation

Halophytes that colonize salt marshes have ability to withstand a sediment environment characterized by high salinity and have a well-developed aerenchyma system through which atmospheric oxygen is transported from the leaves to the roots. The oxygen not consumed by root respiration is available for diffusion into surrounding sediment, promoting change of chemical properties, mainly redox status and pH, which condition the availability of trace metals. In addition, the solubility and availability of metals in marshes, in general, and for vegetation in particular, may be affected by other factors, such as concentration and speciation of metals. The characteristics of the sediment are also of major importance, including the grain size, organic matter content, biotic aspects, concentrations of inorganic and organic ligands including plants exudates, cation exchange capacity, etc.

Therefore, mutual interactions between plants and surrounding chemical environment which determine the role-played by plants on trace metal distribution and uptake, may vary among plant species and, for a single plant, among locations with different characteristics.

According Padinha et al., (2000) the dominant producer of the lower salt marshes in Ria Formosa is the small cordgrass *Spartina maritima* (Poales: Poaceae), which is a pioneer specie in the lower marsh areas with a typical zonation forming clear homogeneous stands (Figure 7.2). *S. maritima* is an European cordgrass which has an important role as a primary colonist of intertidal mud flats since it is able to trap and stabilize sediment efficiently, thus facilitating successional development. Its upper limit is typically by subsequent invasion of *Arthrocnemum perenne* (Castillo et al., 2000). In SW Iberian Peninsula *S. maritima* dominates many lower marshes with anoxic sediment exposed to high inundation periods (Castillo et al., 2008). *Spartina* marshes are among the most productive ecosystems in shallow coastal marine environments (Barnes & Hughes, 1995). Nitrogen fixation associated with the roots and rhizomes of *S. maritima* was 41-650-fold higher than in the bulk sediment (Nielsen, et al., 2001). Early studies (in the 1960s) indicated that a *Spartina* marsh in Georgia, was calculated to export 14 kg ha^{-1} of organic matter per tidal flushing during periods of spring tide and 2.5 kg ha^{-1} during neaps (Barnes & Hughes, 1995).

Figure 7.2.
Ilustration of *Spartina maritima* (M. A. Curtis) Fernald.

In the upper *Marim* saltmarsh *Sarcocornia fruticosa* (Caryophyllales: Chenopodiaceae) appears in pure stands normally with less reducing sediments (Padinha et al., 2000; Moreira da Silva et al., 2015) (Figure 7.3). However this high marsh can presents *S. fruticosa* associated with *Halimione* sp. and *Atriplex sp.*. This association reflects the high values of salinity of the lagoonal water throughout the year (35 g/kg) which results from a semiarid precipitation regime and an extremely high renewal rate (80 % and 52 % in spring and neap waters, respectively) every tidal cycles (Andrade et al., 2004). In Family Chenopodiaceae was developed succulence of organs as a mechanism of salt tolerance, with the aim of balancing out ion toxicity created in saline conditions by increasing the total plant water content. As a result of increased growth on the cell size in succulent tissue, a large accumulation of salts is found without any high increase in intracellular salt concentration. The succulence can be expressed in direction of increase in cell size, decrease in extension growth and reduction in surface area per volume tissue. These halophytes accumulate therefore big amounts of salts through their shoots and show the highest degree of succulence (Grigore & Toma, 2007).

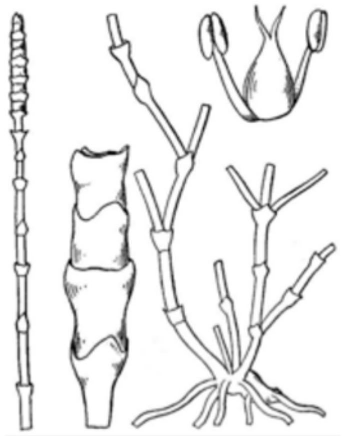

Figure 7.3.
Ilustration of *Sarcocornia fruticosa* (L.) A. J. Scott.

The photosynthetic system CAM (Crassulacean Acid Metabolism) is strongly associated with succulence, and has the advantage not only the reduction in salt uptake but also the possibility of photosynthesis continuing when the plants are submerged by flooding tides and direct gas exchange to the atmosphere is temporarily curtailed, although there are intertidal halophytes with the C_3 pathway (Adam, 1990).

7.3. Metal contents and distribution in sediments of saltmarsh

Non-vegetated sediment can be considered as a sandy sediment, characterized by low fine fraction (FF) in the first 15 cm (1.7-5.8 %), and increasing slightly to deeper layer (max. 12.7 at 30 cm). Aluminium concentration showed a minimum at 5-10 cm, maybe due to the sand transported from nearby clam-culture grounds by tidal currents. The Al content co-varies with the percentage of FF in the sediment at a significant level ($[Al] = 8 \pm 4\ [FF] - 23 \pm 14$; $r = 0.776$; Tukey test, $p < 0.005$). Sediments with high clay content (very fine) have higher aluminium content (aluminosilicates) and, usually higher metal concentrations due to the negative charges of the clay particles. The evolution in the last years of levels of Manganese (Mn), Zink (Zn), Copper (Cu), Chromium (Cr), Nickel (Ni), Lead (Pb), Molybdenum (Mo), Cadmium (Cd) and Silver (Ag), in sediments of *Marim* saltmarsh from surface to 30 cm of depth, showed in surface sediment lower metal contents than deeper, except for Ag, Cd and Mo (Moreira da Silva et al., 2015). This is suggesting the remobilisation of these elements from sediments to water column with the flood tide (Roychoudhury, 2007). The environment at sediment surface is always oxidant, which prevents for instance the formation of metal sulphides that in some cases are unsolvable species. Other possibility is the occurrence of metals downward diffusion into the sediment.

Surface level of Pb observed was higher than those found before in other Ria Formosa sampling areas, not far from *Marim*, indicating the presence of new Pb sources in this area. Industrial plants sited in the surrounding area, like those manufacturing batteries and paints, welding operations, ceramic paints, may be possible sources of Pb, because the effluents of the respective waste water treatment plants are discharged into the *Ria Formosa* with run-off waters. Silver, which was studied by the first time in *Ria Formosa*, presented relatively low levels, between 0.12 and 0.21 mg g^{-1}, depending on the deep. Levels of Mn, Zn, Ni and Cr seemed to have decreased in the last decade while those of Cu and Cd kept approximately constants. The levels of Pb surpassed the respective Effects Range Low being lower than Effects Range Median (Long et al., 1995), indicating that harmful toxicological effect might occasionally occur. According to the Portuguese classification (DR, 2007), the sediment of *Marim* can be considered as trace/lightly contaminated by Pb, Cr and Ni.

7.4. The role of *Spartina maritima* and *Sarcocornia fruticosa* on metal distribution in saltmarsh

Rhizosediments - characteristics and metals contents

Rhizosediment of *S. maritima* was the richest in organic matter, particularly in the first 10 cm depth. In contrast, *S. fruticosa* displayed organic matter depth profile and magnitude rather like that non-vegetated sediments. Enrichment in organic matter at rooting sediment has been usually found (*e.g.* Caçador and Vale, 2001) and is understandable. Entanglement of roots can act as a trap of small and muddy particles from the surrounding sediment, which flows into the rhizosphere of the plants with water during tidal movements. In addition, dead above- and belowground biomass from plants and dead microorganisms that lived in symbiosis with plants may give also an important contribution for the enrichment of rhizosediments in organic matter, namely humic substances, which have high capability of sorption of trace metals, as well as organic and organometallic chemical species. Nevertheless, this study showed that as organic matter trapper and/or producer *S. maritima* was much more efficient than *S. fruticosa*.
Rhizosediment of *S. maritima* was the poorest in silt and clay particles (grain size < 0.063 mm diameter) and, again, only small differences in terms of grain size depth distribution were observed between rhizosediment of *S. fruticosa* and non-vegetated sediment. On the other hand, levels of Si were much

lower in rhizosediment of *S. maritima* than in the other two sediments. The highest Si levels occurred in non-vegetated sediment, the same being observed for Al. However, on the contrary to that happened for Si, *S. maritima* rhizosediment displayed higher Al levels than rhizosediment of *S. fruticosa* [rhizosediment of *S. fruticosa* (0.98 ± 0.19 %) < rhizosediment of *S. maritima* (1.76 ± 0.33 %) < non-vegetated sediment (4.26 ± 0.72 %)]. Together these results indicated some significant differences (Tukey test, $p < 0.005$) amongst the compositions of the sediments. Silicon and organic matter displayed opposite tendencies, which was expected, as Si predominates in sandy sediments whereas organic matter is mainly associated with muddy sediments. Such differences may result of a combination of natural and anthropogenic actions, like the dynamic of the lagoon, dredgings, and presence of specific saltmarsh plants, which condition the preferential retention of certain types of particles. Very distinct redox potential depth profiles were observed. Non-vegetated sediment was anoxic (or reductive). *S. fruticosa* rhizosediment presented positive and relatively high redox potential (oxidative sediment) and rhizosediment of *S. maritima* displayed redox potential in between the other two sites. The release of oxygen by roots can cause a decrease of pH in the rooting zone due to, for instance, sulphide oxidation (S^{2-}/SO_4^{2-}) and Fe^{2+} /Fe^{3+}oxidation followed by Fe^{3+} hydrolisis. In the present case, rhizosediments displayed more acidic conditions than non-vegetated sediment, that is, lower pH values (*S. maritima*: 6.48, 0-5 cm; 6.60, 5-10 cm; 6.70, 10-15 cm depth; *S. fruticosa*: 7.07, 0-5 cm; 7.06, 5-10 cm; 7.02, 10-15 cm depth; non-vegetated: 7.60, 0-5 cm; 7.60, 5-10 cm; 7.70, 10-15 cm depth). These data confirmed results of previous studies, which have showed that more acidic conditions prevail in vegetated sediments than in non-vegetated areas (Caçador et al., 1996; 2000). In all cases some specific variations of redox potential with depth were observed, which are of difficult interpretation. However, it seems clear that the marsh plants could oxidize their rhizosediment in different ways. Visual inspection during sampling showed that main active belowground biomass of *S. maritima* was confined in the first 10 cm depth. In the case of *S. fruticosa* rhizosediment, were observed inorganic precipitates forming rhizoconcretions below 15 cm, which is compatible with the presence of active biomass capable of oxidize the rhizosediment. In addition, *S. fruticosa* showed to have much higher oxidative power than *S. maritima*. Reductive sediment among roots of *S. maritima* and oxidative sediment among roots of *Halimione portulacoides* (another Chenopodiacea) have been also reported by Reboreda & Caçador (2007) for *Tagus* estuary saltmarsh.

The presence of halophyte species changes metal concentration of sediment among roots and that influence is very specific, depending on the plant specie. Much higher level in non-vegetated sediment occurred for Cd: non-vegetated sediment > (5 times higher than) *S. maritima* sediment $\simeq$ *S. fruticosa* sediment (except for depth > 15 cm, where the levels were a little bit high, but still lower than in non-vegetated sediment). Not so drastic differences but still significantly lower levels in rooting sediments of both plants were also found for Mn (only for depth > 10 cm). For other metals, like Cr and Pb, significant and marked differences between rooting sediments of the two plants were observed: metal levels in sediment colonized by *S. fruticosa* were lower than those founded in both non-vegetated and *S. maritima* sediments. Iron occurred in much higher concentrations in rooting sediment of *S. maritima*, whereas *S. fruticosa* rhizosediment displayed levels identical to those of non-vegetated sediment. Significant influence of the plants was not observed for Ag and Mo levels, whereas Zn occurred in much higher concentration in rooting sediments of both plants than in non-vegetated one. Significant differences were found for metal concentrations in depth between non-vegetated sediment, rhizosediment of *S. maritima* and rhizosediment of *S. fruticosa*, except for Cu and Mo.

Metals in Biomass of S. maritima and S. fruticosa

Most of metals coming from surrounding areas to saltmarsh are accumulated in roots of both halophyte species, and also in rhizomes of *S. maritima*. There are significant differences (*Student t-test*, *p <0,05*) in metal concentrations between below- and aboveground parts for all studied metals except for, Fe and Mn in *S. fruticosa* and for Mn in *S. maritima* (Box 7.2).

Box 7.2. How to evaluate the ability for phytoremediation?

To evaluate whether plants can accumulate trace metals in belowground biomass, enrichment factors (EF) can be calculated, EF = Metal concentration in belowground tissues / Metal concentration in rhizosediment.

Enrichment factors higher than 1 have supported the idea that saltmarshes can act as metal phytoestabilizers (Caçador & Vale, 2001; Caetano et al., 2008) thus contributing for decreasing ecosystem metals availability. In *Marim* saltmarsh EF were higher than 1 for Ag, Cd, Mo, Cu, Pb, and Zn, for both halophytes. *S. maritima* displayed lower EF than *S. fruticosa* for Cr, Ni, Zn, Al and Fe and higher for Cu and Pb. Differences in chemical speciation of the different elements, physico-chemical characteristics of the rhizosphere and biomass characteristics, all together will condition the observed results. For instance, *Sarcocornia fruticosa* removed Cr from sediment to roots at all depths, while *S. maritima* didn t show the same behaviour (Moreira da Silva et al., 2015) (Box7.3).

Box 7.3. Why these two halophyte have behave differently in metals remediation?

Why these two halophyte have behave differently in metals remediation? *S. maritima* is a monocotyledonous and *S. fruticosa* is a dicotyledonous, having unlikeness in density and structure of belowground biomass and biological response, these differences in the plant characteristics influence their role in metals remediation.

Once inside the plants, metals can be translocated from belowground vegetal tissues to the aerial organs, leaves and stems for *S. maritima* and chlorophyllin and non-chlorophyllin organs for *S. fruticosa* (Figures 7.4 and 7.5).

Metal translocation (Box 7.4) to both kinds of aboveground organs was significantly higher in *S. fruticosa* than in *S. maritima*, for all metals. The magnitude of translocation for Fe and Mn was very much distinct of that for the remaining studied metals. Iron in aerial organs is closely related to chlorophyll formation and all plants have iron-containing enzymes (Almeida et al., 2005).

Manganese is an activator of a number of enzymes involving in the tricarboxylic acid cycle.

Box 7.4. Is the metal translocation a relevant information to phytoremediation?

Metal translocation to aboveground tissues may be very valuable for phytoremediation of areas where the plants can be cultivated and harvested, thus removing the pollutant from the soil or sediment.

Figure 7.4.
Metal distribution (%) among the roots, rhizomes, stems, and leaves of *S. maritima* (Photo by Nuno Serrano, 2011).

Figure 7.5.
Metal distribution (%) among the aerial chlorophyllin and non-chlorophyllin organs, and roots of *S. fruticosa* (Photo by Nuno Serrano, 2011).

There are few studies on the capacity of saltmarsh species to accumulate and translocated Ag to aboveground tissues. Further efforts are need to study the Ag uptake by other plants, having in mind the possibility of using phytoremediation for cleaning Ag contaminated sediments. Silver residues may occur as result of some industrial activities, such as photographic films and paper, batteries, mirrors, photosensitive glass, etc.

Previous studies (Reboreda & Caçador, 2007) about Cu, Cd, and Pb, concluded that areas colonized by *Halimione portulacoides* (also from Chenopodiaceae family) are potential sources of metals to the marsh ecosystem, *S. maritima* seeming to contribute more effectively to the metal stabilization in saltmarsh sediment (Box 7.5).

During the last decades, wetland plants have been shown to play important roles in constructed wetlands to remove metals from wastewater. Therefore phytoremediation on wetlands can be considered an important type of eco-services to society, based on 'green' technologies and low energy consumption (Min et al., 2007; Rahmana et al., 2014).

Box 7.5. How does metal translocation contribute to its phytoremediation in the saltmarsh?

Metal translocation by halophytic vegetation, may result in a drawback for saltmarsh metal remediation. Metal in aboveground tissues may be accumulated in leaf and stem litter, returning to the marsh system and thus acting as a potential source of metals.

References

Adam, P., 1990. Saltmarsh Ecology. Cambridge Studies in Ecology. Cambridge University Press, Cambridge, 204 p.

Almeida, M.R., Mucha A.P. & Vasconcelos M.T., 2005. The role of a salt marsh plant on trace metal bioavailability in sediments. Estimation by different chemical approaches. *Environmental Science & Pollution Research* 12 (5): 271-277.

Andrade, C., Freitas, M.C., Moreno, J. & Craveiro, S.C., 2004. Stratigraphical evidence of Late Holocene barrier breaching and extreme storms in lagoonal sediments of Ria Formosa, Algarve, Portugal. *Marine Geology* 210: 339-362.

Barnes, R.S.K. & Hughes, R.N., 1995. An introduction to marine ecology. Blackwell Science. Second edition. Hartnolls Ltd, Bodmin, Cornwall.

Caçador, I., Vale, C. & Catarino, F., 2000. Seasonal variation of Zn, Pb, Cu and Cd concentrations in the root-sediment system of *Spartina maritima* and *Halimione portulacoides* from Tagus estuary salt marshes. *Marine Environmental Research* 49:279-290.

Caçador, I., Vale, C. & Catarino, F., 1996. The influence of plants on concentration and fractionation of Zn, Pb and Cu in salt marsh sediments (Tagus Estuary, Portugal). *Journal of Aquatic Ecosystem Health* 5: 193-198.

Caçador, I. & Vale, C., 2001. Salt Marshes. Metals in the Environment. Analysis and Biodiversity. Marcel Dekker, Inc. New York, Basel.

Caetano, M., Vale, C., Cesário R., & Fonseca N., 2008. Evidence for preferential depths of metal retention in roots of salt marsh plants. *Science of Total Environment* 390: 466-474.

Castillo, J.M., Fernández-Baco, L., Castellanos, E.M., Luque, C.J, Figueroa, M.E. & Davy, A.J., 2000. Lower limits of *Spartina densiflora* and *S. maritima* in a Mediterranean salt marsh determined by different ecophysiological tolerances. *Journal of Ecology* 88: 801-812.

Castillo, J.M., Leira-Doce, P., Rubio-Casal, A.E. & Figueroa, E., 2008. Spatial and temporal variations in aboveground and belowground biomass of *Spartina maritima* (small cordgrass) in created and natural marshes. *Estuarine, Coastal and Shelf Science* 78: 819-826.

DR, 2007. Critérios de qualidade de sedimentos. No 217 de 12-11-2007. Diário da República. Online available at: https://data.dre.pt/eli/port/1450/2007/11/12/p/dre/pt/html

Gambrell, R.P., 1994. Trace and toxic metals in wetlands – A review. *Journal of Environmental Quality* 23: 883-891.

Grigore, M.N. & Toma, C., 2007. Histo-Anatomical Strategies of *CHENOPODIACEAE* Halophytes: Adaptive, Ecological and Evolutionary Implications. *WSEAS Transactions on Biology and Biomedicine* 4 (12): 204-218.

Kennish, M.J., 2001. Practical Handbook of Marine Science. Third Edition. CRC Press, 876 p.

Long, R.E., MacDonald, D.D., Smith, S.L. & Calder, F.D., 1995. Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments. *Environmental Management* 19 (1): 81-97.

Min, Y., Boquing, T., Meizhen, T. & Aoyama, I., 2007. Accumulation and uptake of manganese in a hyperaccumulator Phytolacca Americana. *Minerals Engineering* 20: 188-190.

Moreira da Silva, M., J. Aníbal, D. Duarte & L. Chícharo, 2015. *Sarcocornia fruticosa* and *Spartina maritima* as heavy metals remediators in Southwestern European saltmarsh (Ria Formosa, Portugal). *Journal of Environmental Protection and Ecology* 16 (4): 1468–1477.

Nielsen, L.B., Finster, K., Welsh, D.T., Donelly, A., Herbert, A., Wit, R. & Lomstein, B.A., 2001. Sulphate reduction and nitrogen fixation rates associated with roots, rhizomes and sediments from *Zostera noltii* and *Spartina maritima* meadows. *Environmental Microbiology* 1 (3): 63-71.

Padinha, C., Santos, R. & Brown, M.T., 2000. Evaluation environmental contamination in Ria Formosa (Portugal) using stress indexes of *Spartina maritima*. *Marine Environmental Research* 49: 67-78.

Padmavathiamma, P.K. & Li, L.Y., 2007. Phytoremediation Tecnholoy: Hyper accumulation Metals in Plants. *Water Air Soil Pollution* 184: 105-126.

Rahmana K.Z., Wiessner B. A., Kuschk B. P., Afferdena, M. V., Mattuschc J. & Müller A. A., 2014. Removal and fate of arsenic in the rhizosphere of *Juncus effusus* treating artificial wastewater in laboratory-scale constructed wetlands. *Ecological Engineering* 69: 93-105.

Reboreda, R. & Caçador, I., 2007. Halophyte vegetation influence in salt marsh retention capacity for heavy metals. *Environmental Pollution* 146: 147-154.

Roychoudhury, A.N., 2007. Spatial and seasonal variations in depth profile of trace metals in saltmarsh sediments from Sapelo Island, Georgia, USA. *Estuarine, Coastal and Shelf Science* 72: 675-689.

8. Human impact in the Ria Formosa lagoon

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8.1. What is this chapter about?

The Ria Formosa lagoon is a complex, economic, social-ecological system that provides valuable ecosystem services and benefits for the region. Nevertheless, the presence of hazardous substances such as metals, persistent organic compounds (POPs), polycyclic aromatic hydrocarbons (PAHs) and emerging contaminants, including personal care products (PCPs) and pharmaceutical compounds, is a cause of concern for the sustainability of the lagoon. It can be concluded that the Ria Formosa lagoon is in danger, therefore management decisions need to be taken to reduce discharges and enable remediation. These will both protect and depollute, in order to decrease the impact of the mixtures of hazard substances and improve economic sustainability in the future.

8.2. Impacts of the Human activities in Ria Formosa

The Ria Formosa lagoon is a complex, economic, social-ecological system that provides valuable ecosystem services and benefits to the resident population and visitors (Newton et al., 2013; Newton et al., 2018). Nevertheless, some human activities in and around the Ria Formosa introduce contaminants (see Box 8.1) and hazardous substances (see Box 8.2) to the lagoon, degrading the environmental and ecological status of this important ecosystem.

In this chapter, we analyze the relationship between the causes and consequences of this degradation using a DPSIR approach (see Box 8.3). Looking first at the high-level DRIVERS, the Ria Formosa and catchment are important for food security. The area surrounding the lagoon, the 'Campina de Faro' is now increasingly urbanized, but there is still some agricultural activity. This is mainly production of citrus, corn, almonds and red fruits, including hydroponic production. There is some intensive agriculture in greenhouses, which are easily visible from satellite photographs (Figure 8.1). Animal rearing, both on land (poultry and pigs) and in the lagoon (fish) are also important. Food capture includes shellfish harvesting and fisheries. In particular, shellfish harvesting in the Ria Formosa represents 80-90% of total bivalve production of Portugal. The bivalves grow and breed in the intertidal areas of the lagoon that are directly influenced by the different pressures. Salt extraction remains an important industry as can be seen from satellite and aerial photographs (Figure 8.2). There are also large areas devoted to leisure, such as golf courses and swimming pools.

Box 8.1.

Contamination: Introducing any substance into water decreases its purity. So, putting lemon into a glass of water is a contamination, even if it is harmless.

Pollution: If the substance that is introduced into the water is harmful, such as a poison, then this is considered to be pollution and has recently be designed as hazardous substances.

Figure 8.1.
Satellite view showing greenhouses and salt pans between Faro and Olhão (Google Earth, 2018).

Figure 8.2.
Aerial photograph showing salt extraction (photograph by Tomasz Boski, 2009).

So, the main economic sectors and corresponding stakeholder groups around the lagoon include sand and salt extraction, agriculture, animal rearing, aquaculture, fisheries, food processing, golf, tourism, and real estate. The increase of waste production from these result in consequent pressures to the lagoon. Not all activities from these economic sectors result in the release of hazardous substances to the lagoon, but some do. The inputs of these various substances reach the lagoon by atmospheric deposition, river discharges, agriculture and road runoff, runoff from golf courses, sewage effluent, effluent from animal rearing and aquaculture industrial effluent, effluents and emissions from harbours marinas and boats. In addition, there is marine litter from fishing and tourism.

Box 8.2. Hazardous Substances and Priority Substances

What is the difference between Priority Substances, Hazardous Substances and Priority Hazardous Substances? Contaminants and pollutants are grouped in several categories as Hazardous Substances (https://www.ospar.org/work-areas/hasec/chemicals); Priority Substances and Priority Hazardous Substances (Directive 2008/105/EC).

Hazardous substances: Substances or groups of substances which are either (i) toxic, persistent and liable to bioaccumulate; or (ii) assessed by OSPAR as giving rise to an equivalent level of concern

Priority Substances: 33 substances or groups of substances for which environmental quality standards were set in Directive 2008/105/EC.

Priority Hazardous Substances: a subset of Priority Substances, of which they are the most dangerous. They are characterised by their persistence, bioaccumulation and toxicity, or by an equivalent level of concern.

What types of substances contaminate and pollute the Ria Formosa?

Nutrients and organic matter: these mainly come from fertilisers and animal wastes, including sewage, as well as food processing. They are not toxic but promote algal and bacterial blooms that can affect the water quality, especially clarity and oxygen.

Metals (Cd, Cr, Cu, Hg, Pb and Zn) occur naturally in the marine environment. Some like cadmium, mercury and lead are highly toxic and therefore are considered priority substances in the Water Framework Directive. Others like copper and zinc are essential to biota. In excessive amounts, they become toxic and even at lower levels they can affect the immune systems or the reproductive success of biota. Cadmium is used in batteries, paints, combustion plants, electroplating and incinerators. Mercury is applied in electrolysis chlor-alkali plants, combustion plants and gold exploitation. Lead and organic lead compounds were used in fuel for internal combustion engines, paint and as PVC (Polyvinyl chloride) stabilizer. For the essential metals, Cu is extracted from copper mining, and used in electric wiring, machinery, antifouling paints and in pesticides while zinc is used in combustion plants; surface treatment of sheet metal and cosmetics.

Tri-Butyl Tin (TBT): is an organotin compound found in the marine environment from different sources, but mainly from antifouling paint coatings of ship hulls and from agricultural runoff. Once released to the marine environment, TBT partitions between the dissolved phase or is adsorbed onto suspended particulates and settles in sediments, becoming bioavailable to biota through a combination of these compartments and from contaminated food. The effects include shell malformation in oysters, which reduces growth. TBT also causes imposex in neogastropod whelks, turning females into males by superimposition of male characters - a penis and a vas deferens- onto females of gonochoristic gastropods. This causes a population decline in the whelks.

Persistent organic pollutants (POPs): In contrast with metals, POPs are not natural compounds and are made by humans. They include in their composition carbon, hydrogen with halogens like chlorine or bromine or other halogens that resist to degradation. Some are used as biocides (insecticides, herbicides, etc.) while others are used in industrial processes. They are included in the Stockholm Convention on Persistent Organic Pollutants; a legal mechanism established to control the production and use of POPs. Among them 12 POPs should be banned or strictly controlled and further 10 POPs were subsequently included.

Polycyclic aromatic hydrocarbons (PAHs): PAHs are compounds consisting of benzene rings with carbon and hydrogen and, in some cases nitrogen, oxygen or sulphur. Unlike POPs, they occur naturally and can be created by imperfect combustion processes. Some of them are carcinogenic and/or can affect the reproductive system.

Contaminants of emerging concern: In this category Personal Care Products (PCPs), pharmaceutical compounds and micro and nanoparticles are included. PCPs include substances used for personal health or cosmetic reasons. Nanoparticles are particles whose size range from 1-100 nm. They can be metal, metal oxide or carbon based.

Endocrine disruptors: Endocrine disruptors are exogenous substances or mixture of substances that can alter the endocrine system and consequently causes adverse health effects in an organism.

Due to the restricted circulation within the inner part of the lagoon (only 70% of the water is daily exchanged with the Atlantic Ocean), many of the hazardous substances discharged from the land or from the atmosphere concentrate within the lagoon and the blind ends are particularly affected. Only the regions with direct access to the sea, such as the principal shipping channels (from Farol and Olhão channels) are routinely flushed, but these channels receive oil and other contaminants from shipping activities.

Box 8.3.

The analysis follows a Driver-Activity-Pressure-State-Impact on Human welfare approach, modified from the DPSIR (Driver-Pressure-State-Impact-Response) framework, (Gari et al., 2015) according to Elliott et al. (2017). The DPSIR framework has been chosen for this analysis because it was selected by many international institutions, such as the European Environment Agency (EEA), the Food and Agriculture Organisation (FAO) and recently by the United Nations (UN) as the basis for the second World Ocean Assessment.

8.3. What are contaminants and where are they coming from?

Contaminants include nutrients, especially from fertilisers containing Nitrogen and Phosphorus, which can result in eutrophication (Newton et al., 2003). Inputs of organic matter, for example from sewage, increase the Biochemical Oxygen Demand and can result hypoxia or anoxia.
The Ria Formosa lagoon receives the discharge of effluents from 28 domestic and industrial wastewater treatment plants (WWTPs), twelve of which release their effluents directly to the lagoon (Figure 8.3).

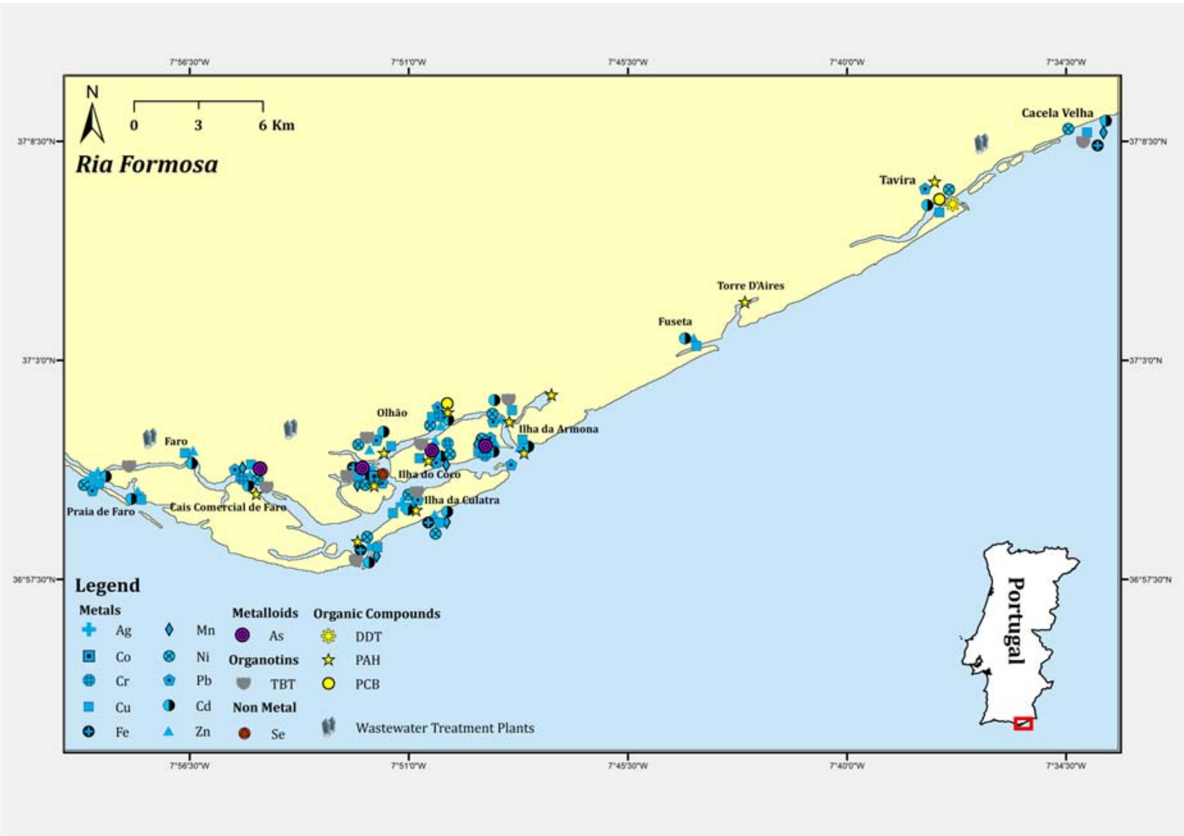

Figure 8.3.
The different hazardous substances detected in the lagoon.

Treatment of domestic sewage was insufficient until the middle 90s. However, sewage treatment has now improved so domestic sewage is treated in urban waste water treatment plants (UWWTP) using secondary treatment (activated sludge + UV and lagoon systems) serving a population equivalent of around 300 000 inhabitants. Sewage contamination in the lagoon has been monitored and detected including using lipid biomarkers such as cholesterol (Mudge et al., 1998). Pressures from nutrient and organic matter inputs can result in a change of environmental status, such as low oxygen, and ecological status, such as excessive algal blooms (Figure 8.4).

Figure 8.4.
Flushing of the Ria Formosa. The blue channel at the back is well flushed, whereas the water in the area at the forefront has been trapped for several days, time enough for an impressive algal bloom to develop (Photograph by Stephen Mudge, 2005).

8.4. What are hazardous substances and what are their impact on living resources?

Hazardous substances include metals and organometallic compounds, persistent organic compounds (pesticides), hydrocarbons, personal care products, pharmaceuticals and plastics. These have been detected in the Ria Formosa water, sediments and biota, posing serious risks to the biodiversity, to the economic development of the lagoon and to human health (see Box 8.2 for definitions). These adverse effects include acute toxicity, a threat to food safety and other impacts to human health such as an increase of cancer cases, weakness of the immune system, reproductive alterations and mutations in future generation.

Hazardous substances like metals (Cd, Cu, Cr, Ni, Pb and Zn) (Bebianno, 1995) and polycyclic aromatic hydrocarbons (PAHs) have been detected in water, sediments and bivalve species. The concentration of these hazardous substances is highly dependent on temperature, salinity, pH, tidal cycle, currents and seasonality. To assess the impact of these hazardous substances "canary species" known as sentinel or bioindicator species are used. Examples are the mussels *Mytilus galloprovincialis,* clams *Ruditapes decussatus* and oysters *Crassostrea gigas*, because they integrate the concentration of hazardous substances in space and time and the concentrations are a measure of their bioavailability. However, chemical analysis of concentrations of hazardous substances in bioindicator species does not give information on the biological effects that can affect health. Therefore, it is essential to also determine early warning systems, known as biomarkers, at molecular, cellular and tissue levels to assess the health of the species. In addition, hazardous substances are generally present as mixtures and the assessment of their cumulative impact is crucial to protect the environmental quality of the lagoon and human health. Figure 8.5 shows the different species in which contaminants have been detected.

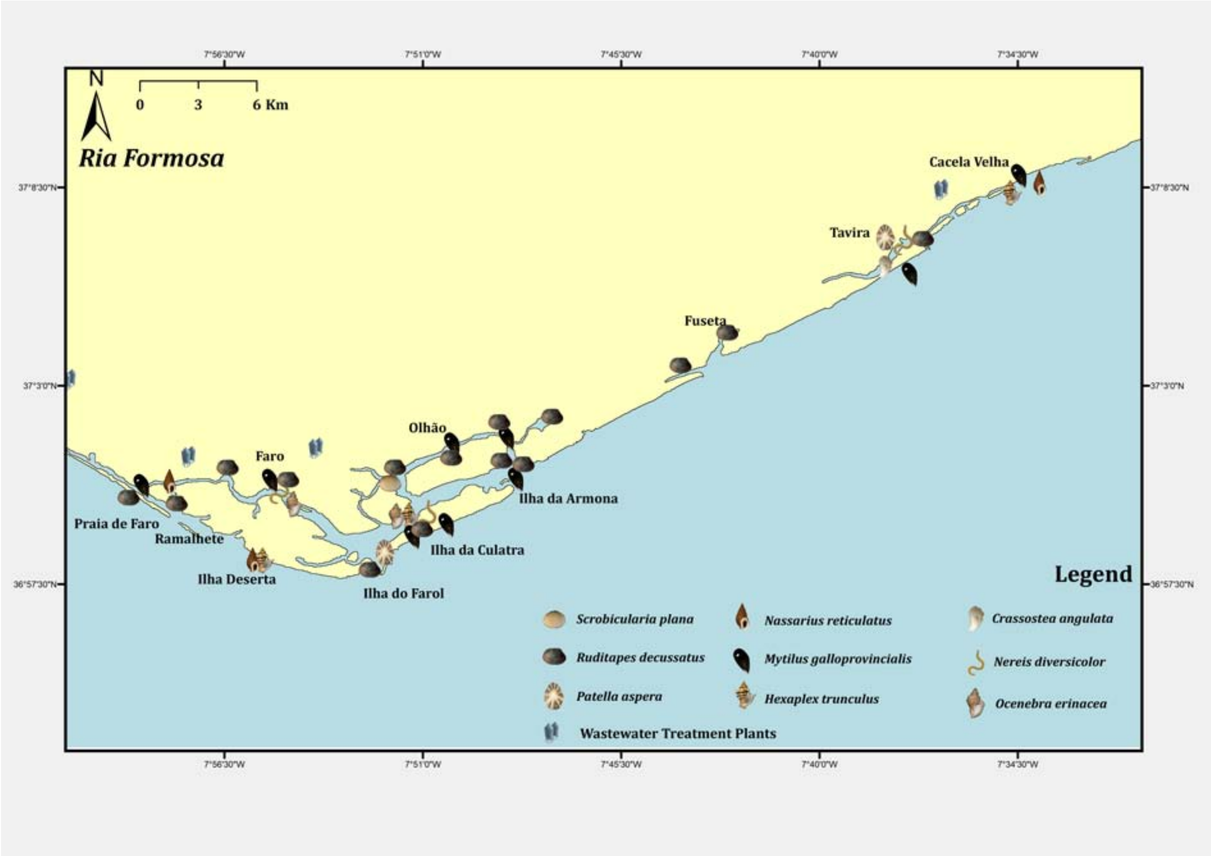

Figure 8.5.
The different species in which contaminants have been detected.

8.4.1. Metals and Tributyltin (TBT)

Among the metals, Cd, Cu, Hg, Pb and Zn are included in the priority list of the Water Framework Directive (additional information about Directive no76/464/CEE is available at_https://eur-lex.europa.eu/legal-content/FR/ALL/?uri=CELEX%3A31976L0464) due to their toxicity, persistence and bioaccumulation. Their presence in the lagoon was first detected in the 1970s, but metal levels were more regularly monitored after the 1990s. The trends for the various metals in the Ria Formosa (water, sediment and bivalves) are summarized in Table 8.1. This also shows the trend for TBT, Tri-Butyl Tin (see Box 8.2).

Table 8.1.
Summary of trends of metals in the Ria Formosa water, sediment and shellfish since the 1970s.

Metal	Water	Sediment	Shellfish	Hotspots
Cd-Cadmium	↘	↘		Near urban centres (Faro and Olhão)
Cu-Copper	↘	↘	↗	Olhão
Hg-Mercury	↔			
Pb-Lead	↔	↘	⌒	Inner parts of the channels
Zn-Zinc	↔	↘	⌒	Olhão, Tavira
TBT	↘	↘	↔	Olhão

8.4.2. Persistent Organic Pollutants (POPs)

This large group of organic substances are banned since 2001 by the Stockholm convention on persistent organic pollutants (POPs). They include many types of pesticides, such as fungicides, herbicides and insecticides, Polychlorinated Biphenyls (PCBs) and Polycyclic Aromatic Hydrocarbons (PAHs). The trends for the various POPs in the Ria Formosa (water, suspended particulate matter and bivalves) are summarized in Table 8.2.

Table 8.2.
Summary of trends of POPs in the Ria Formosa water, suspended particulate matter (SPM) and shellfish.

POPs	Water	SPM	Shellfish	Hotspots
Herbicides	↘	↘		
Fungicides	↘	↘		
General			↘	31% exceed 2008/105/ EC and 98/83/EC
DDT				Still detected although banned in 1970s
Dichlorvos				35 times higher than 2013/39/EU
Heptachlor				80 000 times higher than 2013/39/EU
PCBs	↗			Tavira, Armona
PAHs	↗	↗		Olhão

Pesticides

Organochlorine pesticides used in agriculture are known to induce hormonal disruption and cancer. In the Ria Formosa lagoon, fifty-six pesticides have been detected in water and, in suspended particulate matter. 31% of the pesticides detected exceeded the European directives levels (2008/105/EC and 98/83/EC) (additional information is available https://eur-lex.europa.eu/eli/dir/2008/105/oj and https://eur-lex.europa.eu/ legal-content /EN/TXT/?uri=CELEX%3A31998L0083). However, the data suggest that herbicide contamination is generally decreasing and there is a (2-fold) decrease in fungicides (Cruzeiro et al., 2015). The insecticide dichlorodiphenyltrichloroethane (DDT) has been used extensively worldwide in agriculture and for vector control since 1939 (Turusov et al., 2002). Nowadays, the use of DDT is restricted to disease vector control especially for malaria or as an intermediate in the production of dicofol (Stockholm Convention on Persistent Organic Pollutants, 2008). The major metabolite of DDT is pp'-dichlorodiphenyldichloroethylene (pp'DDE). Thus, despite the ban in the seventies of the last century, DDT/DDE are still marketed and used in many countries, and therefore still extensively widespread in the environment (Lopes et al., 2014). However, recently 4,4-DDT residues (both in dissolved phase and solid phase matter (SPM) detected were higher than its metabolites which indicates a continuous source to the lagoon. Therefore, DDT is still being used, despite of being banned from Europe in the 1970s. Cumulative levels of pesticides (3.1 g/L) were higher than the maximum established by the Portuguese law 236/98 and the 98/83/EC European Directive (water intended for human consumption) (additional information is available https://data.dre.pt/eli/dec-lei/236/1998/08/01/p/dre/pt/html and https://eur-lex.europa.eu/legal-content/EN/TXT/ ?uri=CELEX%3A31998L0083). When comparing the maximum levels (annual values for inland and surface waters) with those defined in the 2013/39/EU directive (additional information is available https://eur-lex.europa.eu/legal-content/EN/ALL/ ?uri=CELEX% 3A32013L0039), dichlorvos and heptachlor were 35- and 80,000-fold higher. The same pesticides were analysed in the whole soft tissues of the suspended feeder peppery furrow shell *Scrobicularia plana* and 83% of the data was above the legal limits set by the European Directive 2013/39/EU (additional information is available https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32013L00 39). As for the other pesticides there was a decreasing trend (5-fold) between 2010 and 2012/2013 (Cruzeiro et al., 2016).

Polychlorinated Biphenyl (PCBs)

Organochlorine compounds comprise a heterogeneous category of highly toxic organic compounds designed for industrial applications. They have been banned or severely restricted since the 1970s and 1980s in North America and Europe due to their persistence and bioaccumulation in the environment, biomagnification in food chains, and capacity for long-range atmospheric transport (Negoita et al., 2003). The main PCBs source appears to be the Gilão river (Barreira et al., 2005; Ferreira & Vale, 1995). Total PCBs are higher in suspended matter than in the sediments, and concentrations are related to the organic matter content and the particle size. These also influence PCB distribution, so the major transport and redistribution are dependent upon the hydrodynamics of the lagoon. About 60% of the total PCBs detected are tri- and tetra-chlorinated biphenyls were the most abundant congeners, followed by the hexa (20%), penta (11%) and hepta+octachlorobiphenyls (9%) (Barreira et al., 2005) while previous data showed that tri- and tetra-biphenyls represented 27%, penta 11%, hexa 40% and hepta and octachlorobiphenyls 22% (specially at Tavira) (Ferreira & Vale, 1995) indicating a dechloronization of the PCBs. Historical data revealed that low concentrations were detected in the whole soft tissues of the oysters and clams. However, recently there is an increasing trend (3.6-fold) in the dissolved fraction of PCBs (Cruzeiro et al., 2015; 2016).

Polycyclic Aromatic Hydrocarbons (PAHs)

PAHs are considered priority organic substances, because they are human carcinogens and toxic to aquatic life. The main sources are urban runoff, atmospheric deposition as well as maritime traffic. PAHs concentrations are directly related to the organic matter content, like for PCBs. Hence, the organic carbon content has a strong influence on the PAH distribution in the lagoon (Barreira et al., 2007). Historically data revealed that the concentration of non-polar hydrocarbons in water varied between 0.5 and 0.6 mg/l, while in sediments, levels ranged from 4 g/g (in 1994) to 30 g/g (in 1998) (IH, 1998). These levels are lower than the ecotoxicological assessment criteria (EAC) set for sediments by OSPAR Commission (OSPAR, 2000) and therefore are considered slightly contaminated (PAHs< 250 ng/g) and have a marked petrogenic origin. In winter, PAH sources are mainly from pyrolytic origin, probably transported by urban runoff while in the summer it is from atmospheric deposition as well as from maritime traffic.
The highest concentration in mussels was from those collected at Olhão. PAH levels in mussels were of the same order of magnitude of those previously found in the south coast of Portugal, but lower than in mussels from areas affected by oil spills or tanker accidents (Cravo et al., 2012).
Like for the other hazardous substances, the consumption of PAH contaminated clams raises concern for human health. Most of the clams analysed are safe for human consumption, except from some particular clam beds with unusually high PAH concentrations, suggesting the need for a regular survey of PAHs levels in clam tissues.

8.4.3. Endocrine Disruptors

Endocrine disruptors include a group of "priority" substances linked to several endocrine disorders in humans. The industrial hazardous substances octyl- and nonylphenoland bisphenol (BPA) were banned in Europe in 2003 (Directive 2003/53/EC additional information is available https://eur-lex.europa.eu/LexUriServ/ LexUriServ.do?uri=OJ:L:2003:178:0024:0027:en:PDF) due to their estrogenic effects to wild fauna and humans. All these compounds are highly hydrophobic and so they adsorb to particulate matter and settle into sediments where their concentrations may be even higher, triggering endocrine disruptor effects to the biota and pose directly (bathing) or indirectly (contaminated seafood) risks for humans.

BPA is ubiquitous in the lagoon, with levels always higher than the maximum established in European legislation for surface waters (10 ng/L). On the other hand, some estrogens like EE2, also present in the lagoon can induce effects in bivalves and fish (Rocha et al., 2013). Feminization of the clam *S. plana* was already reported in the region and there is a cause of concern (Gomes et al., 2009), since this could have a negative impact on the economically important shellfish and the long-term sustainability of the lagoon. The main inputs of estrogens into the lagoon are from human and animal excretion transported by WWTPs effluents or from runoff. Levels are higher in the summer indicating that these compounds are linked to the increased population from visitors and touristic activities. The new WWTP that is being built might change the situation, so there is a need for a continuous monitoring programme.

8.4.4. Personal Care Products (PCPs)

Personal Care Products (PCPs) have been recognized as important organic contaminants of the aquatic environment due to their lipophilic properties and their potential for bioaccumulation (European Parliament, 2007). They have recently attracted attention due to their widespread use and the negative impact they have in the aquatic environment. PCPs include UV filters used in cosmetics and sunscreens to prevent chemical degradation and skin damage against sunlight irradiation. They also include synthetic musks used in fragrance ingredients and as washing and cleaning agents, which also have a potential endocrine disruption effects in marine organisms. Three UV filters (EHMC, OC and OD-PABA) and a musk (galaxolide) have been detected in mussel tissues from a beach outside the Ria Formosa lagoon (Picot Groz et al., 2014).

8.5. Impact on human health

Humans are exposed to multiple substances that can have hazardous effects on health. Numerous hazardous substances can be transported by the food chain and contaminate the food sources for human consumption. In this context, metals, PCBs, PAHs and organochlorine pesticides are among the most important contaminants to be considered. Although the levels of hazardous substances in Ria Formosa in both biotic and abiotic compartments have been identified, it is largely unknown the impact of these substances on the health of local human populations. Exposure to different pollutants is assessed by biomonitoring of blood serum, urine, adipose tissue, meconium, milk, placenta, hair and nails.

Over the past two decades numerous studies have linked the exposure of pregnant mothers to hazardous substances to several diseases in the newborn children. These hazardous substances can pass through the placenta, via the umbilical cord, and into the newborn children. The vulnerability of newborn children derives from both rapid development and incomplete defense systems. Children face amplified, lifelong risks from their body burden of these hazardous substances. The consequences can surface not only in childhood but also in adulthood.

8.5.1. Metals

The global increase of metals in the environment, their tendency to accumulate in humans, and their potential to be toxic even at low concentrations raise special concern about adverse effects on sensitive

segments of the population such as newborns. The health risks associated with in utero exposure to metals were studied extensively in the last few decades. In fact, there is increasing evidence regarding the threats posed on pregnancy outcomes and/or adverse developmental effects at levels lower than international guidelines, and therefore environmental exposures need to be as low as possible.
Toxic metals may act as mimics of essential metals, binding to physiological sites that normally are reserved for an essential element. Through mimicry, they may gain access to, and potentially disrupt, a variety of important or even critical metal-mediated cellular functions. Mimicry for and replacement of Zn is a mechanism of toxicity postulated for cadmium (Cd), cooper (Cu), and nickel (Ni) (Cousins et al., 2006). Another mechanism of metal toxicity is based on oxidative damage to important cellular components.
Research studies in the IN-Health cohort (Project In-Health - Materno-Infant health related to environmental factors (PTDC/SAU-SAP/121684/2010)) with women living in south of Portugal, at the major cities of the Ria Formosa, identified non-essential metals with recognized toxicity (Cd, Hg and Pb) in all mother and umbilical cord samples, indicating that these metals have the capacity to circulate in the blood stream and/or transpose the placenta, reaching the fetus. Spatially, Cd levels were higher in women from Faro and Olhão relatively to Tavira. Contrarily, the highest Hg levels were detected in women from Tavira while Pb levels were elevated in women from Olhão. Although the south coast of Portugal is not a heavily industrialized area, metal levels found in these populations are at the same order of magnitude as those found by other authors in European countries (Serafim et al., 2012). The data are summarized in Table 8.3.

8.5.2. Persistent Organic Pollutants (POPs)

Pesticides

These compounds are highly persistent to degradation or metabolism. They are highly lipophilic so tend to accumulate in adipose tissues. Furthermore, they are suspected potent endocrine disrupters. Although banned, they continue to be manufactured by many other countries, and the presence of these hazardous substances in human serum, milk and adipose tissue have been reported (Cruz et al., 2003). For the general population, the greatest exposure to pesticides is from food intake. Since many of the chemicals are soluble in fat, the highest levels are found in meat, fish and dairy products. Little is known about the possible effects of pesticides in humans when exposed for long periods of time to small concentrations, but evidence of mother to child transfer has been reported. On the other hand, leukemia, non-Hodgkin's lymphoma and other cancers, neurologic pathologies, respiratory symptoms and hormonal and reproductive abnormalities have been associated with pesticide exposure, mostly in case-control and ecological studies. Human prenatal exposure to organochlorine pesticides has been associated to adverse developmental effects, including preterm birth and reduced birth weight, growth retardation, altered psychomotor and cognitive functions and effects on thyroid hormonal status (Asawasinsopon et al., 2006).
In Portugal, according with the legislation (Decreto-Lei nº 347/88 and Portaria nº 660/88) (additional information is available https://dre.tretas.org/dre/1709/decreto-lei-347-88-de-30-de-setembro#in_links and https://dre.tretas.org/dre/163955/portaria-660-88-de-30-de-setembro) most of the organochlorine pesticides were prohibited in 1980s, but they can be found in the environment even decades after being banned (Cruz et al., 2003). In the south of Portugal, they have been extensively used as pesticides in orange groves and greenhouses, and some authors have reported the presence of pesticides in the rivers and groundwaters of Portugal, primarily in association with the wide range of agricultural practices (Palma et al., 2014).

Levels of ***DDE***, the major metabolite of DDT was found in women living in the south of Portugal, whose main path of exposure and therefore accumulation is diet. Levels of DDE were highest in women living in Tavira (1.61 ng/ml mother/ 1.17 ng/ml newborn), followed by Olhão (1.06 ng/ml mother/ 0.79 ng/ml newborn) and Faro (0.98 ng/ml mother/ 0.76 ng/ml newborn) (Lopes et al., 2014).
Drines: Aldrin, dieldrin and endrin have been used as pesticides in agriculture. Although there are different routes of exposure for humans, it has been established that ingestion of food contributes more than 90% of total human exposure, and that the fatty fraction represents the main entrance to the human body. Aldrin is toxic to humans; the lethal dose of aldrin for an adult man has been estimated to be about 5g, equivalent to 83 mg/kg body weight (Hanley et al., 2002). Signs and symptoms of aldrin intoxication may include headache, dizziness, nausea, general malaise, and vomiting, followed by muscle twitchings, myoclonic jerks, and convulsions. Occupational exposure to aldrin, in conjunction with dieldrin and endrin, was associated with a significant increase in liver and biliary cancer (Taylor et al., 1996). Dieldrin is ubiquitous in breast milk and it is found in more than 99% of samples tested in most countries. Because dieldrin is attracted to fat, the level of dieldrin in a mother's milk is generally about six-fold higher than in the blood. WHO found, surprisingly, that the concentration of dieldrin in the blood and bodies of breastfeeding babies did not increase with age during their first six months of life.
In the IN-Health cohort aldrin, dieldrin and endrin were found in all mother and newborn babies. Aldrin presented the highest concentrations, representing about 62-73% of total –drins (-drins=aldrin+endrin+dieldrin), followed by endrin and dieldrin. Overall concentrations of –drins detected in mother and umbilical cord serum were higher in Olhão (9.56 ng/ml mother/ 9.12 ng/ml newborn; aldrin accounts for 62/62 % of total) and Faro (9.37 ng/ml mother/ 8.89 ng/ml newborn; aldrin accounts for 67/66 % of total), and minimum at Tavira (8.70 ng/ml mother/ 9.0 ng/ml newborn; aldrin accounts for 73/66 % of total) (data not published).
The ban of ***hexachlorobenzene*** (HCB**)** as a fungicide led to a significant decrease in its environmental concentration, but it is still being used in the chemical industry and is a by-product of chlorinated solvent production. Moreover, some of the HCB in the soil evaporates into the air, so it is likely that people will be exposed to this compound at levels similar to the current concentrations for some time. Although exposure to HCB in the general population decreased in recent years, there is some evidence of an association between exposure and fetal growth abnormalities and/or reduction in the length of gestation (Basterrechea et al., 2014). Levels of HCB found in people living in the south of Portugal were similar in Faro and Olhão (0.29 ng/ml mother/ 0.22ng/ml newborn and 0.29 ng/ml mother/ 0.20 ng/ml newborn, respectively, and lower in Tavira (0.11 ng/ml mother/ 0.10 ng/ml newborn) (not published).
Endosulfan **(**a dienic compound containing atoms) is still used in several industrialized countries, as it is indicated both in non-food crops, such as cotton and tobacco, timber, and ornamental cultures, and in food crops, such as vegetables, fruits, corn, cereals, oilseeds, potatoes, tea, coffee, cacao, and soy bean. They were also used to control termites and tsetse fly in the past (Cerrillo et al., 2005).
In the South of Portugal, levels of Endos (=alpha+beta+ether+lactone) where similar in Faro (12.50 ng/ml mother/ 11.62ng/ml newborn), Olhão (12.73 ng/ml mother/ 12.51 ng/ml newborn) and Tavira (12.88 ng/ml mother/ 13.17 ng/ml newborn). However, at all sites endosulfan alpha is the major metabolite both in mothers as in newborns, varying from 3.69 to 4.10 ng/ml and representing 29 and 32% of Endos, followed by endosulfan lactone, beta and ether, with minimum concentration varying from 0.68 to 0.92 ng/ml.
Vinclozolin, [3-(3,5-dichlorophenyl)-5-methyl-5-vinyl-oxazolidine 2,4-dione], is a widely used fungicide in fruits, vegetables and wines. It is one of several dicarboximide fungicides currently registered for use in the United States of America and in Europe (U.S. Environmental Protection Agency, 2003). Vinclozolin is a potent androgen antagonist and a cytotoxic compound with endocrine disruption capabilities. Whereas vinclozolin itself is not persistent, it's two metabolites display half-lives of more than 180 days and are

likely to be highly mobile in the water phase. There is little data available on human exposure to vinclozolin in and its possible effects on reproductive health. However, in an occupational study, where the morbidity of the personnel involved in the synthesis and formulation of this chemical was thoroughly investigated, an increase in testicular abnormalities was reported in the study group compared with controls (Zober et al., 1995).
Levels of vinclozolin of 2.02/1.75 ng/ml were found in women/newborn from the IN-Health cohort living in Faro; 2.0/1.61 ng/ml in women/newborn from Olhão and 1.50/1.89 ng/ml in women/newborn from Tavira. The data are summarized in Table 8.3.

Polychlorinated Biphenyl (PCBs)

Food intake is probably the most important source of PCB for the general population, and the consumption of fat rich foods (eggs, cheese, milk, butter, meat, fish and seafood) is one of the most commonly causes of PCB increase found in humans. Health effects associated with exposure to PCBs include skin conditions, liver diseases in adults and neurobehavioral and immunological changes in children, reduced birth weight and pre-term birth.
Three congeners of PCBs (138, 153 and 180) were found in the IN-Health cohort, in all samples of both mother and umbilical cord serum. Overall highest levels of PCBs found in these cohort (PCBs=PCB138+PCB153+PCB180) were found in women that live in Tavira (PCBs 1.78 ng/ml mother/ 1.54 ng/ml newborn) followed by those women that live in Olhão (PCBs1.58ng/ml mother/1.46 ng/ml newborn) and Faro (PCBs 1.50 ng/ml mother/1.33 ng/ml newborn). Strong relationships were found between maternal and umbilical serum PCBs concentrations, indicating equilibrium within the maternal-fetal unit. Residence and surrounding environment, diet and smoking habits appear to be the most significant factors contributing to both maternal and fetal exposures (Lopes et al., 2014). The data are summarized in Table 8.3.

Table 8.3.
Summary of concentrations of hazardous substances in mothers and new-borns around the Ria Formosa.

Hazardous Substances	**Mothers**	**New-Borns**	**Hotspots**
Cd (mg/l w.w.)	0.64	0.43	Faro-Olhão
Hg (mg/l w.w.)	0.56	0.48	Tavira
Pb (mg/l w.w.)	0.47	0.44	Olhão
DDE (ng/l w.w.)	1.61	1.17	Tavira
∑Drins (aldrin, dieldrin and endrin)	9.56	9.12	Olhão
HCB (ng/l w.w.)	0.29	0.22	Faro-Olhão
∑Endosulfan	12.88	13.17	Tavira
Vinclozolin (ng/ml w.w.)	2.02	1.75	Faro
PCBs (ng/l w.w.)	1.78	1.54	Tavira

8.6. Conclusions

From the data presented and the hydrodynamics of the Ria Formosa it can be concluded that lagoon is subject to multiple pressures from contaminants and hazardous substances, some of which have been banned for decades. Management measures and remediation steps need to be put in place to reduce discharges to protect and depollute, as well as to decrease the impact of mixtures of hazardous substances. This is necessary to protect food security and important natural resources such as the shellfish, and to protect the health of the population, especially pregnant mothers and children. These management measures should be complemented by a toxicological monitoring programme, as established by the descriptor 8 of the Marine Framework Strategy Directive.

Acknowledgments

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References

Asawasinsopon, R., Prapamontol, T., Prakobvitayakit, O., Vaneesorn, Y., Mangklabruks, A. & Hock, B., 2006. The association between organochlorine and thyroid hormone levels in cord serum: a study from northern Thailand. *Environment International* 32(4):554-559.

Barreira, L., Bebianno, M.J., Mudge, S.M., Ferreira, A.M., Albino, C.I. & Veriato, L.M., 2005. Relationship between PCBs in suspended and settled sediments from a coastal lagoon. *Ciencias Marinas* 31(1B):179-195.

Barreira, L., Mudge, S. & Bebianno, M.J., 2007. Oxidative stress in the clam *Ruditapes decussatus* (Linnaeus, 1758) in relation to Polycyclic Aromatic Hiydrocarbon body burden. *Environmental Toxicology* 22(2):203-221.

Basterrechea, M., Lertxundi, A., Iñiguez, C., Mendez, M., Murcia, M., Mozo, I., Goñi, F., Grimalt, J., Fernández, M., Guxens, M. & INMA project, 2014. Prenatal exposure to hexachlorobenzene (HCB) and reproductive effects in a multicentre birth cohort in Spain. *Science of the Total Environment* 466–467:770-776.

Bebianno, M.J., 1995. Effects of pollutants in the Ria Formosa Lagoon, Portugal. *Science of the Total Environment* 171(1-3):107-115.

Picot Groz, M., Martinez Bueno, M.J., Rosain, D., Fenet, H., Casellas, C., Pereira, C., Maria, V., Bebianno, M.J. & Gomez E., 2014. Detection of emerging contaminants (UV filters, UV stabilizers and musks) in marine mussels from Portuguese coast by QuEChERS extraction and GC–MS/MS. *Science of the Total Environment* 493:162-169.

Cerrillo, I., Granada, A., Lopez-Espinosa, M.J., Olmos, B., Jimenez, M., Caño, A., Olea, N. & Olea-Serrano, M.F., 2005. Endosulfan and its metabolites in fertile women, placenta, cord blood, and human milk. *Environmental Research* 98(2):233-239.

Cousins, R.J., Liuzzi, J.P. & Lichten, L., 2006. Mammalian zinc transport, trafficking, and signals. *Journal of Biological Chemistry* 281(34):24085-24089.

Cravo, A., Pereira, C., Gomes, T., Cardoso, C., Serafim, A., Almeida, C., Rocha, T., Lopes, B., Company, R., Medeiros, A., Norberto, R., Pereira, R., Araújo, O. & Bebianno, M.J., 2012. A multibiomarker approach in the clam *Ruditapes decussatus* to assess the impact of pollution in the Ria Formosa lagoon, South Coast of Portugal. *Marine Environmental Research* 75:23-34.

Cruz, S., Lino, C. & Silveira, M.I., 2003. Evaluation of organochlorine pesticide residues in human serum from an urban and two rural populations in Portugal. *Science of the Total Environment* 317(1-3):23-35.

Cruzeiro, C., Pardal, M.A., Rocha, E. & Rocha, M.J., 2015. Occurrence and seasonal loads of pesticides in surface water and suspended particulate matter from a wetland of worldwide interest - the Ria Formosa Lagoon, Portugal. *Environmental Monitoring and Assessment* 187(11): 669.

Cruzeiro, C., Rodrigues-Oliveira, N., Velhote, S., Pardal, M.A., Rocha, E. & Rocha, M.J., 2016. Development and application of a QuEChERS-based extraction method for the analysis of 55 pesticides in the bivalve *Scrobicularia plana* by GC-MS/MS. *Analytical and Bioanalytical Chemistry* 408(14):3681-3698.

Elliott, M., Burdon, D., Atkins, J.P., Borja, A., Cormier, R., De Jonge, V.N. & Turner, R.K., 2017. "And DPSIR begat DAPSI (W) R (M)!"- A unifying framework for marine environmental management. *Marine pollution bulletin* 118(1-2):27-40.

European Parliament 2007. Legislative resolution of 22 May on the proposal for a directive of the European Parliament and of the Council on environmental quality standards in the field of water policy and amending Directive 2000/60/EC (COM(2006)0397-27).

Ferreira, A.M. & Vale, C., 1995. The importance of runoff to DDT and PCB inputs to the Sado estuary and Ria Formosa. *Netherlands Journal of Aquatic Toxicilogy* 29(3-4):211-216.

Gari, S.R., Newton, A. & Icely, J.D. 2015. A Review of the application and evolution of the DPSIR framework with an emphasis on coastal social-ecological systems. *Ocean & Coastal Management* 103:63-67.

Gomes, T., Gonzalez-Rey, M. & Bebianno, M., 2009. Incidence of intersex in male clams, *Scrobicularia plana,* in the Guadiana Estuary, Portugal. *Ecotoxicology* 18(8):1104-1109.

Hanley, G.D., Beblo, D.A., Wohlers, D., Avallone, A., Bosch, S. & Plewak, D., 2002. Toxicological profile for Aldrin and Dieldrin. U.S. Department of health and human services. Public Health Service Agency for Toxic Substances and Disease Registry. 354 p.

Instituto Hidrográfico, 1998. Contribuição do Instituto Hidrográfico para a elaboração do capítulo 4 do Relatório do Estado da Qualidade da Região IV da Comissão de Oslo e Paris. Setembro, 51p.

Lopes, B., Arrebola, J.P., Serafim, A., Company, R., Rosa, J. & Olea, N., 2014. Polychlorinated biphenyls (PCBs) and p,p'-dichlorodiphenyldichloroethylene (DDE) concentrations in maternal and umbilical cord serum in a human cohort from South Portugal. *Chemosphere* 114:291-302.

Mudge, S.M., East, J.A., Bebianno, M.J. & Barreira, L., 1998. Fatty acids in the Ria Formosa Lagoon, Portugal. *Organic Geochemistry* 29:963-977.

Negoita, T.G., Covaci, A., Gheorghe, A. & Schepens, P., 2003. Distribution of polychlorinated biphenyls (PCBs) and organochlorine pesticides in soils from the East Antarctic coast. *Journal of Environmental Monitoring* 5(2):281-286.

Newton, A., Icely, J.D., Falcão, M., Nobre, A., Nunes, J.P., Ferreira, J.G. & Vale, C., 2003. Evaluation of eutrophication in the Ria Formosa coastal lagoon, Portugal. *Continental Shelf Research* 23:1945-1961.

Newton, A., Brito, A.C., Icely, J.D., Derolez, V., Clara, I., Angus, S., Schernewski, G., Inácio, M., Lillebø, A.I., Sousa, A.I., Béjaoui, B., Solidoro, C., Tosic, M., Cañedo-Argüelles, M., Yamamuro, M., Reizopoulou, S., Tseng, H.C., Canu, D., Roselli, L., Maanan, M., Cristina, S., Ruiz-Fernández, A.C., deLima, R.F., Kjerfve, B., Rubio-Cisneros, N., Pérez-Ruzafa, A., Marcos, C., Pastres, R., Pranovi, F., Snoussi, M., Turpie, J., Tuchkovenko, Y., Dyack, B., Justin Brookes, J., Povilanskas, R. & Khokhlov, V., 2018. Assessing, quantifying and valuing the ecosystem services of coastal lagoons. *Journal for Nature Conservation* 44:50-65.

Newton, A., Icely, J.D., Cristina, S., Brito, A., Cardoso, A. C., Colijn, F., Riva, S.D., Gertz, F., Hansen, J.W., Holmer, M., Ivanova, K., Leppakoski, E., Canu, D.M., Mocenni, C., Mudge, S., Murray, N., Pejrup, M., Razinkovas, S., Reizopoulou, S., Pérez-Ruzafa, A., Schernewski, G., Schuber, H., Carr, L. C., Solidoro, C., Viaroli, P. & Zaldívar, J.M., 2013. An overview of ecological status, vulnerability and future perspectives of European large shallow, semi-enclosed coastal systems, lagoons and transitional waters. *Estuarine, Coastal and Shelf Science* 140:95-122.

OSPAR Commission, 2000. Quality Status Report 2000, OSPAR, London. Online available at: https://qsr2010.ospar.org/media/assessments/QSR_2000_Region_II.pdf

Palma, P., Köck-Schulmeyer, M., Alvarenga, P., Ledo, L., Barbosa, I.R., López de Alda, M. & Barceló, D., 2014. Risk assessment of pesticides detected in surface water of the Alqueva reservoir (Guadiana basin, southern of Portugal). *Science of the Total Environment* 488-489:208-219.

Rocha, M. J., Cruzeiro, C., Reis, M., Rocha, E. & Pardal, M., 2013. Determination of seventeen endocrine disruptor compounds and their spatial and seasonal distribution in Ria Formosa Lagoon (Portugal). *Environmental Monitoring and Assessment* 185:8215-8226.

Serafim, A., Company, R., Lopes, B., Rosa, J., Cavaco, A., Castela, G., Castela, E., Olea, N. & Bebianno, M.J., 2012. Assessment of essential and non-essential metals and different metal exposure biomarkers in the human placenta in a population from the South of Portugal. *Journal of Toxicology and Environmental Health*, 75(13-15): 867-877.

Stockholm Convention on Persistent Organic Pollutants (POPs), 2008. United Nations Environment Programme. Online available at: http://chem.unep.pops.int

Taylor, J., Spoo, J.W. & Kedderis, L.B., 1996. Toxicological profile for endrin. U.S. department of health and human services. Public Health Service Agency for Toxic Substances and Disease Registry. 227 p.

Turusov, V., Rakitsky, V. & Tomatis, L., 2002. Dichlorodiphenyltrichloroethane (DDT): ubiquity, persistence, and risks. *Environmental Health Perspectives* 110(2):125-128.

U.S. EPA., 2003. Vinclozolin; notice of filing a pesticide petition to establish a tolerance for a certain pesticide chemical in or on food. *Fed. Regist*. 68:14628-14635. Online available at: http://www.epa.gov/fedrgstr/EPA-PEST/2003/March/Day-26/p724631

Zober, A., Hoffmann, G., Ott, M.G., Will, W., Germann, C. & van Ravenzwaay, B., 1995. Study of morbidity of personnel with potential exposure to vinclozolin. *Occupational and Environmental Medicine* 52:233-241.

9. Marine energy prototype testing at Ria Formosa

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9.1. Renewable energy, a world urgent need

Economic growth and increasing human demands are among the most important factors for growing world energy consumption. Energy is present in everything around us: it is a property of all objects and is essential to life. We find various forms of energy in the world around us. When plants grow, for example, they are converting sunlight energy into chemical energy in the form of carbohydrates and other compounds stored in your body (e.g. sugars). The form of energy that man uses most today is the chemical energy contained in fossil fuels, such as oil, coal and natural gas. About 80% of the energy we use comes from these sources. However, these sources are very polluting, since their use releases substances harmful to the environment and to public health. An example of this is the increased concentration of greenhouse gases such as carbon dioxide (CO_2) in the atmosphere, which is a cause of climate change. In addition to pollutants, these sources of energy are non-renewable, which means that they are being consumed at a faster rate than is necessary for their production, so their availability is decreasing.
Due to the increasing oil and natural gas prices, reduced fuel reserves and the requirement for reduced CO_2 emissions to avert climate change, the use of alternative energy sources is both financially unavoidable and environmentally preferable (UN, 2015). Hence, generating renewable energy is nowadays one of the most relevant endeavours for research. Countries worldwide now recognise the need to incorporate renewable energy resources in their energy policy as an alternative to finite fossil fuel resources in order to achieve future energy security and to mitigate the effects of climate change induced by human activities. Today, renewable energy is now firmly entrenched as the world's fastest growing energy sector (IEA, 2017).

9.2. EU priority to become carbon neutral in 2050

The EU has set objectives to become a smart, sustainable and inclusive economy by 2020 (EREC, 2010; EC, 2011). The EU objective are to cut 20% of greenhouse emissions, 20% increase in energy efficiency and 20% of energy produced using renewable sources. To accomplish those objectives each of the EU countries had to establish individual targets and action plans; as well as collaborate with each other's on joint project in energy share. The challenges of transforming Europe's energy system remain urgent and daunting: the EU currently imports approximately 55% of its energy – and might reach 70% in the next 20 to 30 years. In 2030 the EU will be importing 84% of its gas, 59% of its coal and 94% of its oil. Only 8.5% of the energy market of the 28 European countries is from renewable energy sources (EREC, 2010). In these circumstances, it is obvious that the challenge to satisfy our energy needs is urgent and most European governments have introduced schemes to encourage the development and uptake of renewable energy, either through direct grants or by introducing favourable tariffs for electricity generated from renewable sources.
The European Commission is looking at cost-efficient ways to make the European economy more climate-friendly and less energy-consuming. The roadmap (European Commission COM12, 2011) suggests that, by 2050, the EU should cut its emissions to 80% below 1990 levels through domestic reductions alone (milestones to achieve this are 40% emissions cuts by 2030 and 60% by 2040). To reach this goal, the

EU must make continued progress towards a low-carbon society where clean technologies play an important role.

9.3. The huge untapped source for clean energy production, the sea

The oceans cover 70% of the planet Earth and are composed of huge masses of water of different characteristics in constant movement as result of the interaction Ocean-Atmosphere. This constant movement can produce virtually inexhaustible energies: marine renewable energies (MRE). The MRE' resources are categorized based on which properties of the ocean are used, such as motion, heat or salinity. There are 6 forms of MRE: offshore wind, tidal potential energy (e.g. tidal barrage/lagoons), tidal kinetic energy (e.g. ocean currents), wave energy, and energy produced by thermal or salinity gradients (Figure 9.1).

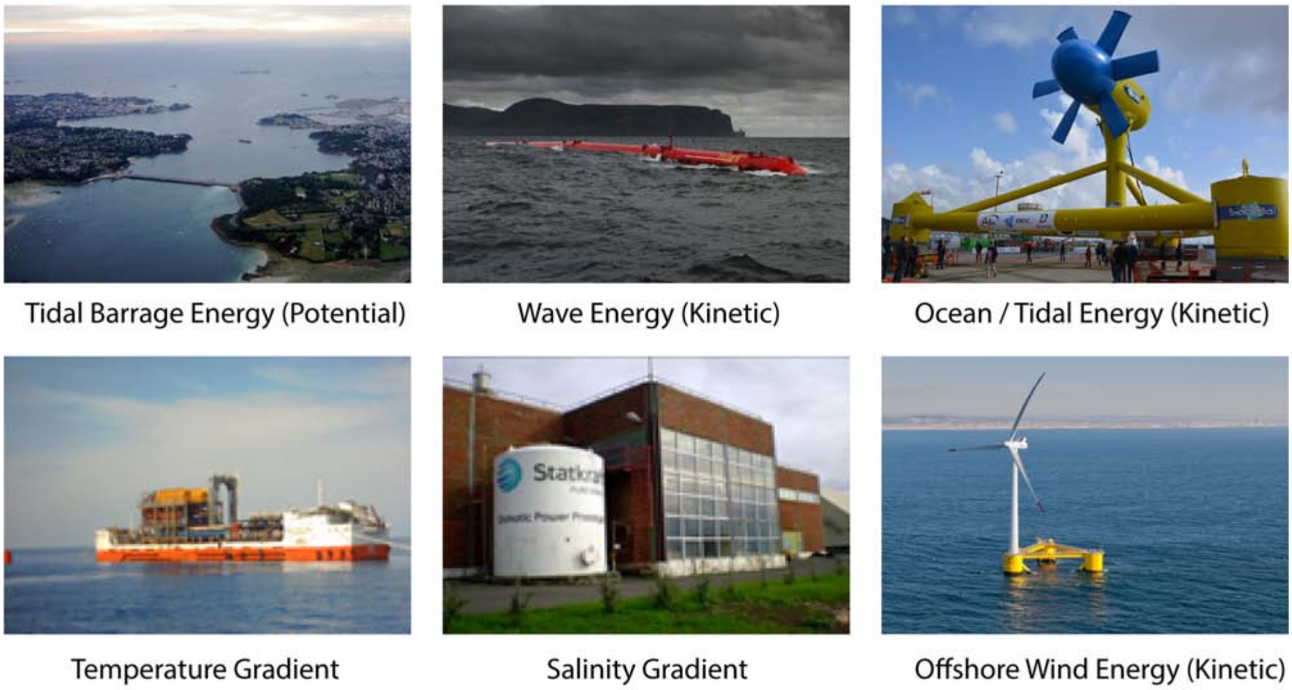

Figure 9.1.
Different forms to extract energy from ocean processes: tidal barrages/lagoons, wave devices, tidal turbines, temperature/salinity power plants and offshore wind platforms (e.g. Windfloat Project, Portugal). These energy resources have the potential to be an alternative for global energy production, compared to oil resources and nuclear power plants. Despite the high potential for solving some of the world's energy requirements, technologies for marine energy extraction are at an early stage of development, so their use is not yet economically viable.

Marine renewable energy sector offers the opportunity for a balanced, consistent and sustainable social and economic development of the whole Europe. The existing estimates is that the harvestable energy from the World's Ocean is equal to twice the amount of electricity produced in the World today (World Energy Council, 2016). Currently, MRE has the potential to satisfy approximately 15% of the present European electricity demand and the EU is currently the market leader (Table 9.1). This huge potential as a clean green source of power could provide a substantial amount of the total electricity demand by 2050, as well as help to cut carbon emissions and support thousands of jobs reducing unemployment and encouraging social cohesion (European Commission COM12, 2011). Whilst the majority of work to date has focused on the wind and solar sectors, the generation of electricity from waves, tidal currents and tidal range has received renewed interest as some of the complexities of practically harnessing other forms of renewable energy become apparent.

Table 9.1.
European objectives for electric production using marine energy resources (Source: ***European Marine Board*** & ***International Energy Agency – Ocean Energy Systems***)

European Objectives	Offshore Wind	Tidal Energy	Wave Energy
Electric Production (TWh/year)	563(2030)	36(2040)	142(2040)

Despite the global financial crisis, the ocean renewable energy sectors in Europe have received €80m of European Commission (EC) funding and over €680m private investment in the last 7 years (European Ocean Energy 2013; SI Ocean, 2014; EWEA, 2014). The investment to date in offshore renewable energies has shown growth across the maritime sectors and throughout the supply chain (SI Ocean, 2014). Survey companies have expanded, professional services and design consultants have been commissioned, vessel operators have diversified, and offshore contractors have undertaken significant work (Figure 9.2).

Figure 9.2.
A new offshore wind prototype, Starfloat. Offshore wind is today the renewable energy sector with the fastest growth in Europe. By 30 June 2013 European waters contained 1,939 offshore wind turbines (capacity 6040 MW) in 58 wind farms across 10 countries (IEA, 2017) (source: OceanFlow Energy Ltd).

The European Commission is fully engaged in the development of offshore marine renewable energies. Under the Research Framework Programme, the cumulated EC contribution over the last fifteen years is above 20 million €. Meeting the EU's new binding targets for marine renewable energy would lead to a net increase of 410,000 jobs in the EU by 2020 (European Ocean Energy, 2013). However, progress towards cost-competitiveness will depend on creating the right market environment and investment decisions across Europe for the future. By addressing regulatory challenges, the sector can bridge the gap to commercialisation and make a significant contribution towards growth, employment and decarbonisation throughout the EU.

9.4. Portugal potential on the marine energy sector

At a European level, Portugal can be considered a pioneer in testing and connecting marine renewable energy to the grid. The natural potential of the Portuguese coast and the conditions arising from the proximity of technology infrastructure support, the fixed fee for electricity produced and the knowledge acquired in the area of utilisation of these energies are significant comparative advantages that the country can enjoy with great benefit, both in terms of production of renewable electricity, technology development, products and services exported to other regions of Europe and the world. Those factors has encouraged the first offshore wave projects to be sited in Portuguese waters. One of the first pilot wave station was set in Pico (Açores) and the first offshore wave project array was sighted in Portuguese waters (Pelamis, Aguçadoura). The marine renewables are a priority of the National Strategy for the Sea (DGPM, 2012), reinforced by the National Action Plan for Renewable Energy 2020 (PNAER, 2011). However, the capacity to attract marine renewable devices in Portuguese waters dropped considerable, despite the natural potential of the Portuguese coast and the conditions arising from the proximity of technology infrastructure support, the fixed fee for electricity and the knowledge acquired. Today, Portugal has solely one prototype in the water, an offshore wind device, the Windfloat (Figure 9.1). To invert this situation, the European Commission approved a new support scheme launched by the Portuguese Government so that Portugal would be able to support wave energy projects and wind offshore technologies. This state support translates into a guaranteed energy purchase tariff for 25 years in order to offset the higher costs of new technologies. The scheme will support demonstration projects for a total installed capacity of 50 MW, 25 MW of which have already been allocated to the Windfloat project. The remaining 25 MW capacity will be allocated to different promoters / projects (https://www.edp.com/en/windfloat).

9.5. Tidal energy

Of all marine renewable energy sources, tidal energy is one of the greatest forces on Earth with vast potential as a major renewable source and can play a key role in global energy production in the near future. Tidal energy is the energy dissipated by tidal movements, which derives directly from the gravitational and centrifugal forces between the Earth, the Moon and the Sun (Figure 9.3). Tidal energy can be predicted for centuries, both from the point of view of time of occurrence and magnitude, is clean and does not run out, in contrast to the unpredictability of other renewable energies, such as wind, solar, waves, etc.

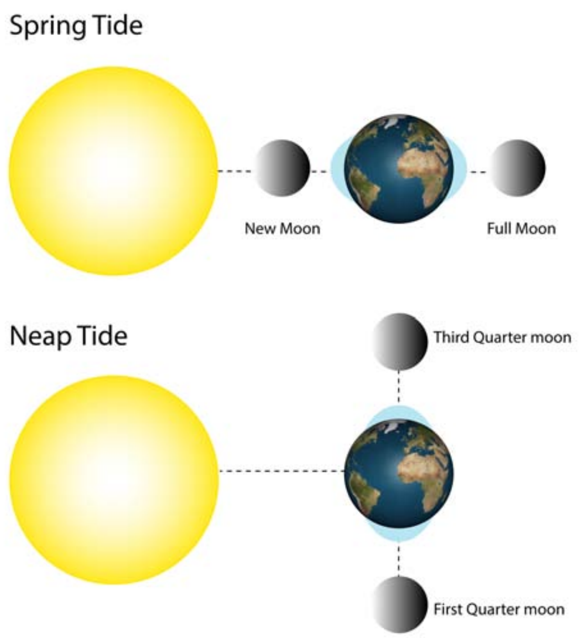

Figure 9.3.
The tides are changes in mean sea level: water rises when the tide is filling; and descends when the tide is dropping. This rise and fall of the water level occurs because the gravitational forces of the Moon (which has greater influence because of being so close to the Earth) and the Sun attract the water masses of the Oceans towards them, forming a tidal wave. As tides are caused by gravitational forces, the amplitude of the tides (i.e. varying height between low tide and high tide) depends on the relative position between the Earth, the Moon and the Sun. If all are aligned, for example, their gravitational forces add up and the amplitude of the tide is greater - it is at these times that we have Spring-tides! If they are misaligned, the amplitudes of the tides are smaller and we have the so-called Neap-tides.

The world tidal power resource (i.e. tidal potential and tidal kinetic energy) is estimated to be 3 TW, with 1 TW located in relatively shallow waters. However, due to geographical, technical and environmental constraints only a fraction of this could be captured in practical terms (World Energy Council, 2016). In practice, suitable locations need mean spring peak tidal currents that are faster than 2-2.5 ms^{-1} to offer an energy density that allows for an economically viable project. For example, at the European level 106 locations with a strong tidal stream potential were identified, together offering 48 TWh/yr of potential resource (World Energy Council, 2016).

Tidal energy provides excellent long-term potential for economic growth, energy security and job creation. According to European Ocean Energy (2013), by 2050, Europe could have up to 100 GW of wave and tidal energy installed capacity delivering 260 TWh of clean, affordable and reliable electricity, enough to power 66 million European homes. With up to 337 GW installed around the world, wave and tidal energy could be a multi-billion-euro international industry with significant exports to markets in Asia and across South and North America.

Tidal energy conversion systems can be grouped into 1st generation systems that convert potential energy into electrical energy due to the interaction of two bodies of water during the tide (e.g. tidal barrages, Figure 9.1); and 2nd generation systems that convert the kinetic energy from the movement of the water flow into electrical energy (e.g. tidal turbines, Figure 9.1). First-generation systems require locations with a tidal amplitude greater than 5 m and there are only about 40 sites in the world with such characteristics. Extraction of energy from 2nd generation systems is in an early stage of development, and there is currently no major technology in the market. More than 90 companies are registered in the EMEC European Marine Energy Centre, Orkney Islands in Scotland, with commercial patents in diverse variations of concepts. However, the most mature technology is the horizontal-axis turbine with fixed connexion to the bottom (Figure 9.4) because it resembles wind turbines, and therefore imports direct knowledge of this technology with more than 20 years of sustained commercial implementation in the market. The big difference between the two is the diameter of the blades. Because the water is eight hundred times denser then air, less rotation area is needed to generate the same amount of energy.

Figure 9.4.

(A) SeaGen of Marine Current Turbines (MCT, credit: Siemens AG) was the first commercial scale prototype installed in the world (2008), with a capacity of 1.2 MW (6000 MWh/year - equivalent to the supply of 1500 houses). The company was acquired by the Siemens Group and has planned projects in other UK locations (Kyle Rhea, Anglesey Skerries and Brough Ness, all in the UK) and Bay of Fundy (Canada). However, the first company to test a prototype in open sea condition was (B) OpenHydro (today DCNS group, credit: Mike Brookes-Roper/EMEC) with its 6 m diameter turbine and power generation capacity to supply 150 houses. A tidal turbine functions like a wind turbine under water. The ocean's currents turn the turbine blades. The nacelle has a gearbox inside that increases the speed of rotation and a generator of energy that converts the mechanical into electrical energy. The equipment also has an inverter to transform the produced energy into the voltage needed into the grid. Power estimates are determined by integrating along a Neap-Spring tidal cycle the cube of velocity times the swept area of the turbine, times the water density, times the efficiency factor of each turbine.

Many investors, shareholders, regulators and the public are interested in the potential that the tides have for the production of renewable electricity. The site of the world with the greatest tidal amplitude is the Bay of Fundy in Canada (16 m wide), which means a movement of 160 billion tons of water. This site has enormous potential for tidal energy production, combining both 1st and 2nd generation systems, as there are locations in the bay where the current velocity exceeds 5 m/s. Studies at the University of Acadia in Nova Scotia (Canada) indicate an energy resource of 50 GW only at this location. As far as Europe is concerned, one of the first tide barrages in the World was installed at La Rance in Brittany (France) in 1966 and has a capacity of 240 MW. The tidal amplitude at this location is 8.5 m. Currently, there are several projects for the construction of coastal lagoons off the coast of Wales which aim to create artificial reservoirs in the open seas along the coast. The largest of these projects is Swansea Bay, which installed capacity will be of 240 MW. The largest commercial project planned for Europe is the MeyGen in Scotland at Pentland Firth, which will have an expected installed capacity of 86 MW and aim to reach 398 MW by 2020.

9.6. The environmental effects from exploitation

As above demonstrated, tidal energy can be exploited both by multi-megawatt tidal power farms and mini-power stations with turbines generating a few kilowatts. Such power stations can provide clean energy to small communities or even individual households located near continental shorelines, straits or on remote islands with strong tidal currents. However, despite its potential contribution to world energy demands, tidal energy technologies are currently not economically viable on large scale and are still at an early stage of development. Several devices and equipment have been tested but only a few have become real-scale prototypes, since commercial marine energy development depends largely on the ability of pilot projects to demonstrate the technical, economic and environmental readiness.

The deployment of tidal energy converters has been hindered by a lack of understanding of their environmental interactions, both in terms of the device impact on the environment (important for consenting and stakeholder bodies) and environmental impact on the device (fatigue, actual power output etc., which is vital to enhance investor confidence and increase financial support from the private sector). Most academic research has focussed on hypothetical numerical modelling which is perceived with fairly low confidence by regulatory bodies. In the few cases that devices have been deployed and monitored, the data is highly commercially sensitive and thus not in the public domain to further wider understanding. In order to assuage regulatory bodies' concerns about detrimental environmental impacts, access to freely available, transparently collected monitoring data from real deployments is paramount. Better understanding of device performance is required to draw investment and accelerate commercial scale deployments. Without further research to comprehend these environmental and performance concerns, these issues cannot be definitely resolved and will remain as challenges associated with commercial array deployment.

Extracting tidal energy at commercial scales can potentially have several impacts on the environment such as: to reduce tidal amplitude, to change flow patterns and thus to affect the transport and deposition of sediments, to affect population distribution and dynamic of marine organisms, to modify water quality and marine habitats, to increase ambient noise, and to increase mixing in systems where salinity/temperature gradients are well defined (Neil et al., 2009; Kadiri et al., 2014; Martin-Short et al., 2015). Up until now, no information exists for device arrays of tidal energy converters except some numerical modelling predictions without validation, which are perceived with fairly low confidence by regulatory bodies.

The future prospects for tidal energy converter technologies very much depend on the specific device concept and how those devices can be optimised to efficiently extract energy, minimising environmental impacts. Understanding potential environmental impacts is a key issue in gaining acceptance of new technologies. Primary concerns relating to tidal stream turbine installations are interference with the local ecosystem during installation activities, the potential of the rotating blades to injure fish, diving birds and sea mammals and the loss of amenity, fishing areas and navigation space for other users of the sea area.

9.7. The testing of a floatable tidal energy converter at Ria Formosa

The SCORE project – **S**ustainability of using Ria Formosa **C**urrents **O**n **R**enewable **E**nergy Production – is funded by the Portuguese Foundation for Science and Technology (FCT – PTDC/AAG-TEC/1710/2014) proposed to test for the first time a floatable tidal energy converter on Portuguese waters, the Evopod 1:10th scale prototype from OceanFlow Energy (OE, Figure 9.5). The project brings together a multidisciplinary team, including physicists, oceanographers, geologists, biologists, modellers, marine engineers and economists, and represents a unique opportunity to understand the performance of a floating tethered turbine in energetic tidal flow.

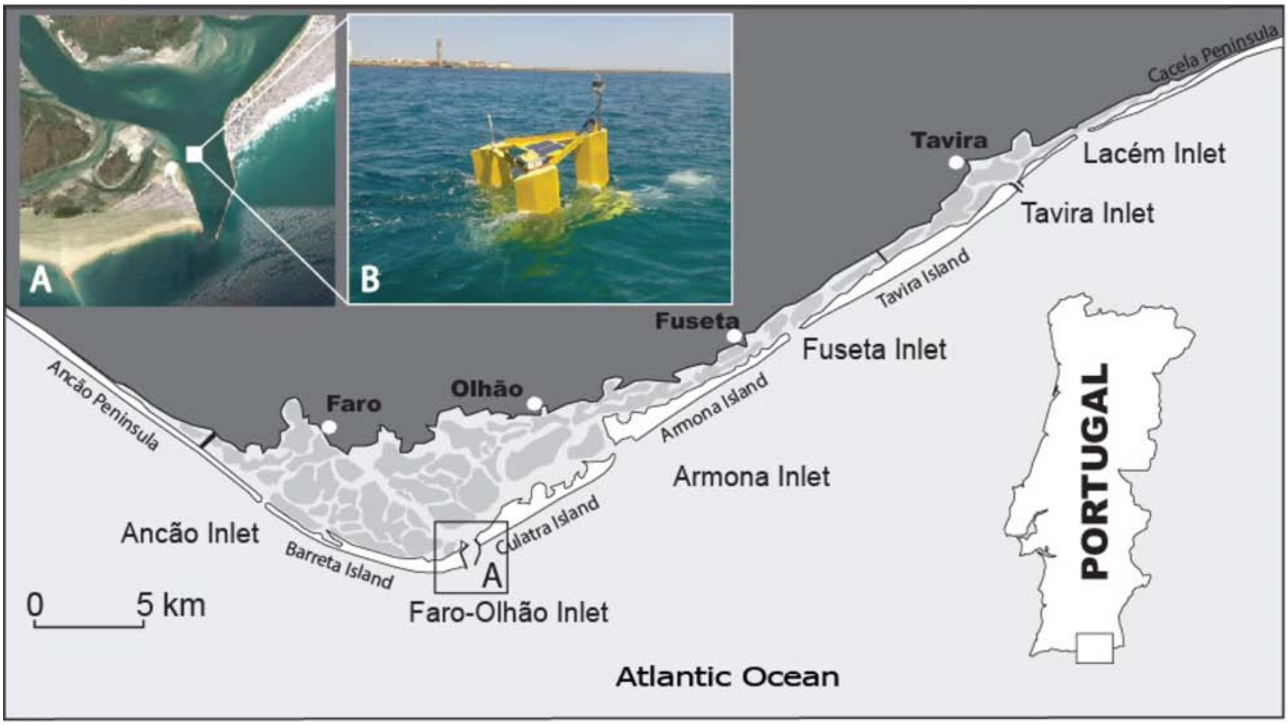

Figure 9.5.
The Ria Formosa system is an ideal place for testing floatable tidal energy converter' prototypes and can be used as representative of the vast majority of coastal areas where these devices can be used in the future to extract energy to power small communities on estuaries and coastal areas. In particular, the Faro-Olhão Inlet, the main inlet of the system, traps 60% of the total spring-tidal prism of the RF system. The inlet is characterised by strong currents and therefore has potential for energy extraction (adapted from Pacheco et al., 2018).

Evopod device is at the technology readiness level (TRL) 7 and a 1:4th scale prototype was tested on Scottish waters on combined ocean-current environment, the requisite required for reaching TRL 8 (i.e. pre-commercial stage) (see Box 9.1). The innovative aspect of testing in Portugal lies with the unique morphological characteristics associated with the device deployment site at Ria Formosa, a coastal lagoon protected by a multi-inlet barrier system located in southern Portugal (Algarve Region). Ria Formosa can be used as representative of the vast majority of shallow coastal areas where tidal energy converters can be used in the future. It is therefore ideal to analyse both the energy extraction efficiency and eventual impacts that extracting energy from the flowing currents will have on the ecological communities and physical settings (Figure 9.5).

Box 9.1. What is a technology readiness level (TRL)?

The TRL was developed by the North American Space Agency (NASA) and is a type of measurement system used to assess the maturity level of a particular technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the projects progress. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest (Figure 9.6).

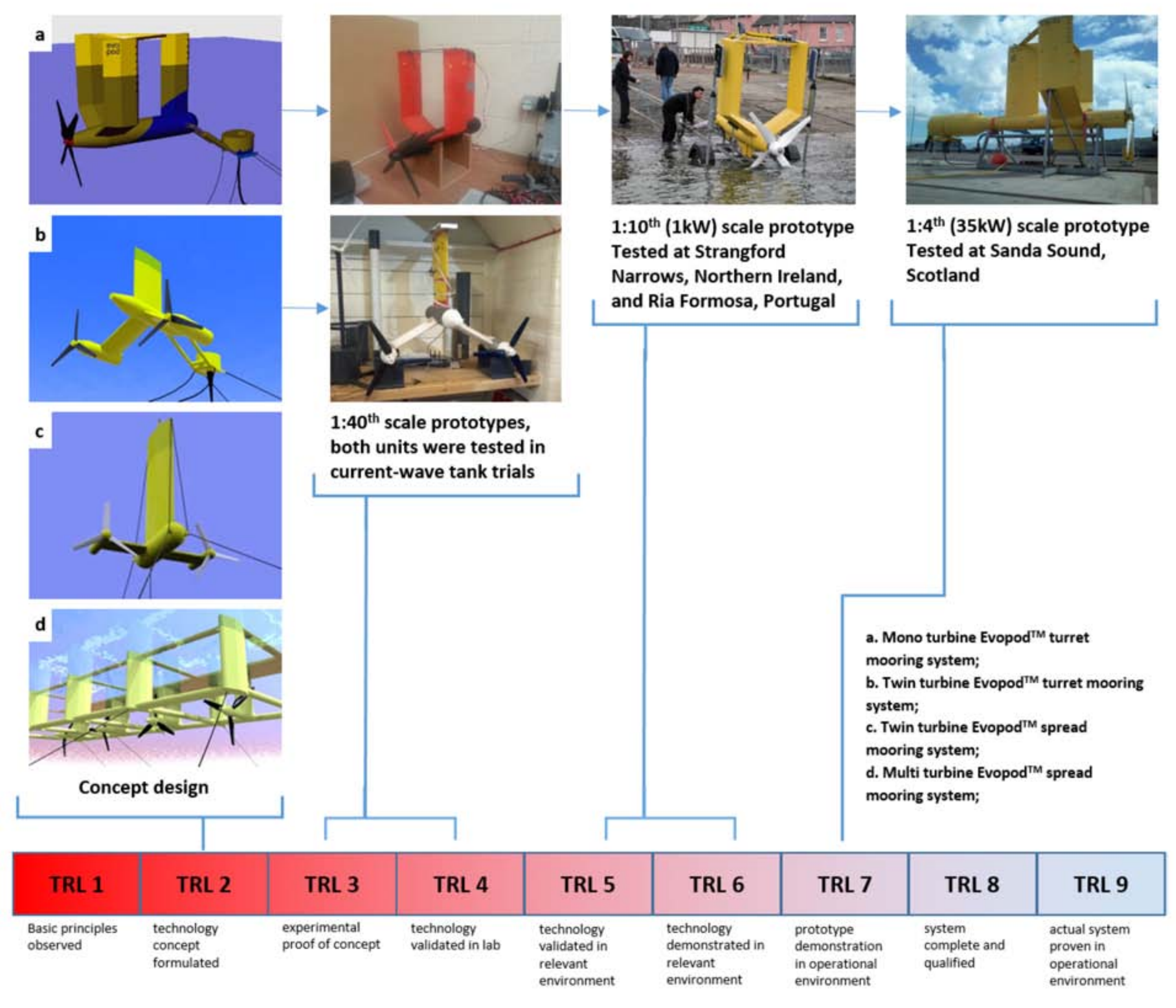

Figure 9.6.
Example of the Evopod™ development path on the Technology Readiness Level (TRL) scale.

Evopod™ is a device for generating electricity from coastal tidal streams, tidal estuaries, rivers and ocean currents (Figure 9.7). It is a unique floating solution drawing upon proven technologies used in the offshore oil / gas and marine industries (Mackie et al., 2008). The 1:10th scale E1 consists of a positively buoyant horizontal cylindrical body of 2 m length and 0.4 m diameter to which are attached three stabilising fins set in a triangle, tethered to the midwater buoy. Each fin is approximately 1.2 m long by 0.1 m and 0.4 m wide. The main body and fins are constructed of steel and painted yellow.

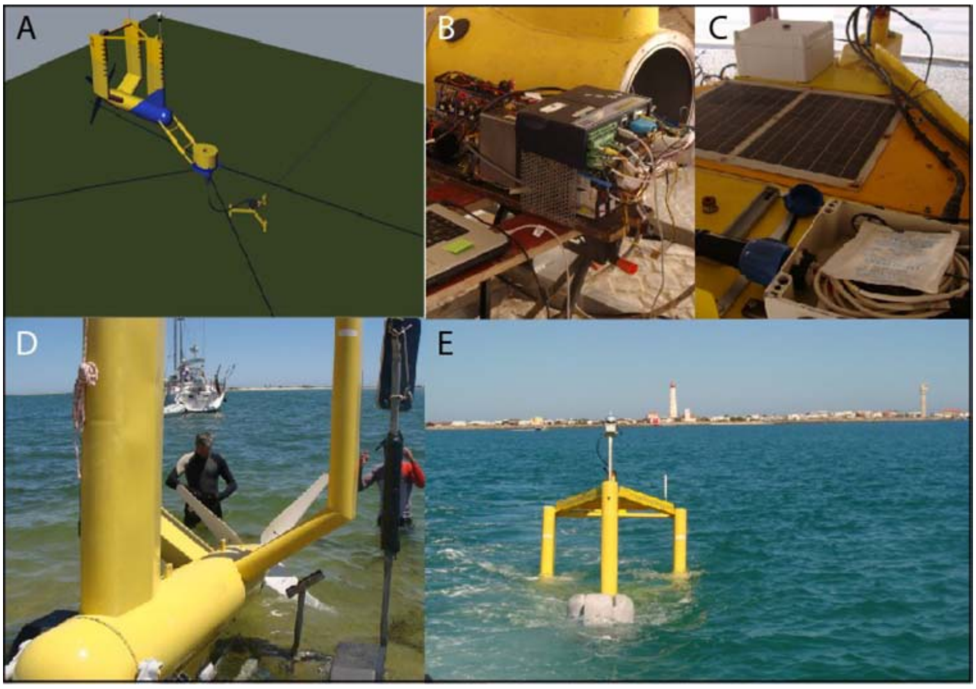

Figure 9.7.
(A) Scheme of Evopod™ with the mooring lines spreading from the mid-water buoy; (B) inside components connect to the logger; (C) detail of the deck with the solar panels and control box; (D) E1 launch on the water and (E) it trawl to the deployment site (adapted from Pacheco et al., 2018).

When deployed, approximately 0.4 m of the three yellow fins are visible above the water surface. A four-bladed 1.5 m diameter turbine made of composite is attached at the rear of the body and is designed to rotate between 20-55 rpm giving a maximum blade tip speed of 4.3 ms^{-1}, driving a 1kW permanent magnet generator. The width of the blade is approximately 0.1 m and the depth between the sea surface and the highest point of the rotor is 0.45 m. The power from the generator feeds the navigation light plus an extensive suite of instrumentation i.e. flow speed, voltage, current, torque, revs, temperature, resistor settings, yaw angle and mooring tension; which are logged and transmitted back to shore over a mobile phone data link. Table 9.2 summarises Evopod key discriminators at different scales.

Table 9.2.
Evopod key parameters (adapted from Pacheco et al., 2018)

	Full scale (Pentland Firth, UK)	**1:10th scale (Stranford Narrow IRL / Ria Formosa, PT)**	**1:40th scale (Newcastle University test tank, UK)**
Length overall (m)	21.5	2.15	0.538
Breadth across struts (m)	13.7	1.37	0.343
Displacement (t)	375,000	375	5.86
Turbine diameter (m)	15	1.5	0.375
Rated output (kW)	1800	0.57	0.004
Rated flow speed (ms^{-1})	4.0	1.26	0.63
Average operating sea state	H_S = 3 mT_Z = 8 s	H_S = 0.3 m T_Z = 2.5 s	H_S = 0.0075 m T_Z = 1.26 s
Survival sea state	H_S = 14 m T_Z = 14 s	H_S = 1.4 m T_Z = 4.43 s	H_S = 0.35 m T_Z = 2.21 s

where H_S is significant wave height and T_Z is the mean zero up-crossing period.

The SCORE team installed the prototype on 8th June 2017 in collaboration with a local company, which was subcontracted to provide a barge boat equipped with a winch (Figure 9.8A), essential to lower the anchoring weights at the exact planned position (Figure 9.8B). The device was tethered to the seabed using a four-line catenary spread mooring system attached to the above mentioned anchoring weights (Figure 9.8C), such that it is free to yaw (weathervane) into the predominant current direction. On each mooring line is placed a load cell (Figure 9.8D) that are measuring the tension while E1 is extracting energy.

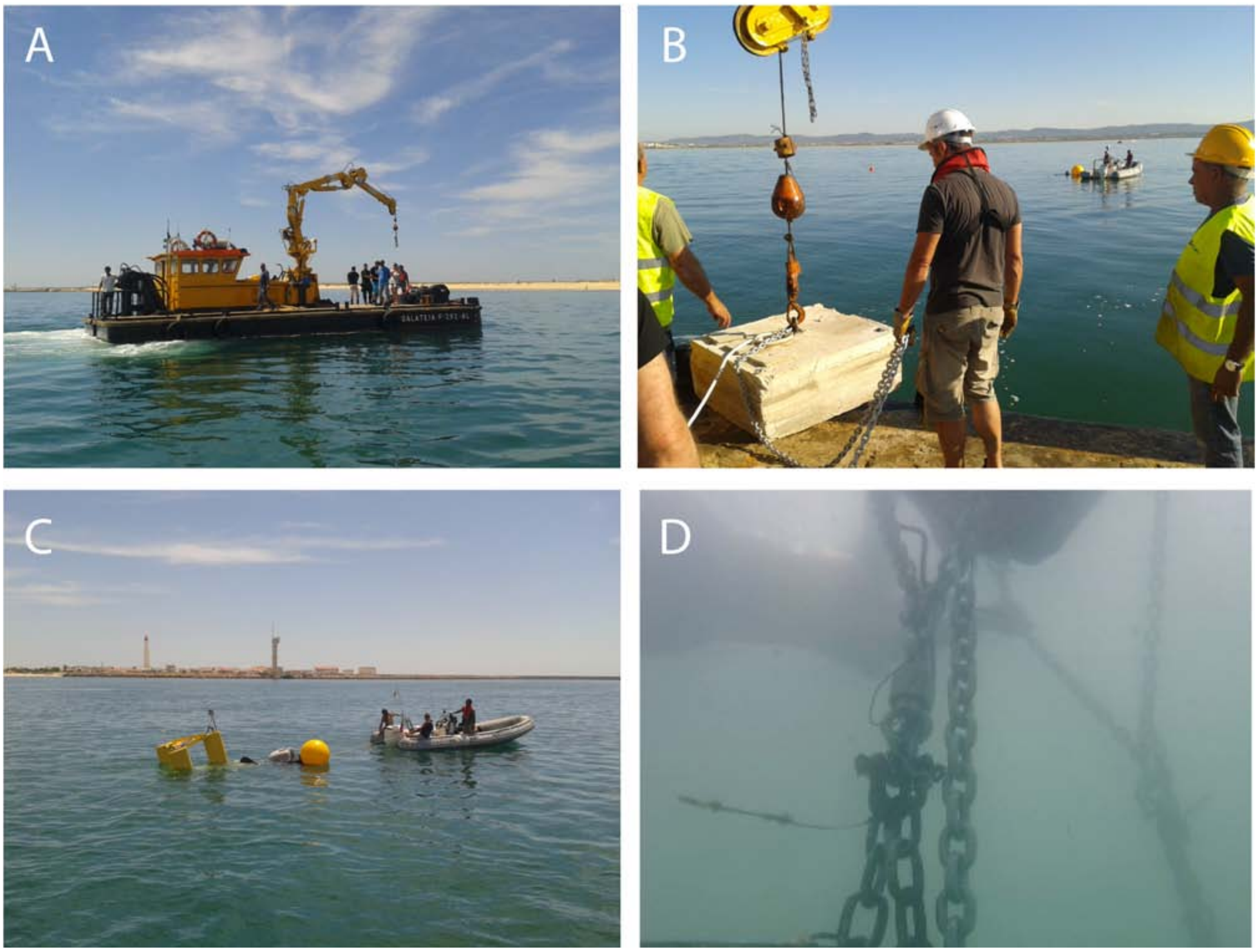

Figure 9.8.
(A) Barge boat equipped with a winch used on the deployment day; (B) mooring operation to lower the anchor weights at the exact plan position; (C) Evopod^{TM} deployed by the divers on 8th June 2017; (D) Load cells on the mooring lines to measure the drag while the device is extracting energy. The entire deployment operation was performed at slack tide and evolved a staff of ten people, including skippers, researchers, divers and technical operators, supervised by the maritime authorities (adapted from Pacheco et al., 2018).

The anticipated flow speeds, wave and wind characteristics at the deployment site used for the design of the mooring system are presented on Table 9.3. The prototype operated at site until the 21st November 2017, when it was towed back to the harbour and removed from the water. All the anchoring system was removed except the anchoring weights that remained on site. In between i.e. period while the prototype was operating, the device had to be removed for maintenance three times, which evolved it subsequent re-installation.

Table 9.3.
Tidal stream, wind and wave characteristics used in mooring design (adapted from Pacheco et al., 2018).

Predicted spring tide peak flow	1.5 ms^{-1}
Percentage time flow exceeds 0.7 ms^{-1}	20 %
Percentage time flow exceeds 1.75 ms^{-1}	0 %
Estimated wind induced surface current	0.2 ms^{-1}
Extreme current speed for mooring design	1.7 ms^{-1}
Wind Direction	NE or NW
Wind Speed	35 $kmhr^{-1}$ (9.7 ms^{-1}or 18.8 knots)
Fetch	4 km (2.2 nautical miles)
Significant wave height H_S	0.45 m
Significant wave period $T_{1/3}$	2.6 s
Mean zero up-crossing period T_Z	2.4 s

The access to freely available, transparently collected monitoring data from real deployments is paramount. The existence of data on environmental conditions prior to extraction of energy on any location will be essential for cataloguing potential impacts of any marine renewable installation. The SCORE data (Pacheco et al., 2018) is now available to the scientific community and to industry developers, enhancing the operational knowledge of tidal technology concerning efficiency, environmental effects, and interactions (i.e. device/environment). An integrated "whole-system" impact monitoring program was implemented while operating the prototype in order to understand environment-device interactions (Figure 9.9). The tidal turbine is also instrumented to continuously monitor and record various parameters. The parameters captured during the Ria Formosa deployment were: flow speed (ms^{-1}), shaft speed of rotation (RPM), generator output voltage and current (Volts), device compass heading (º degree) and mooring tension (kN).

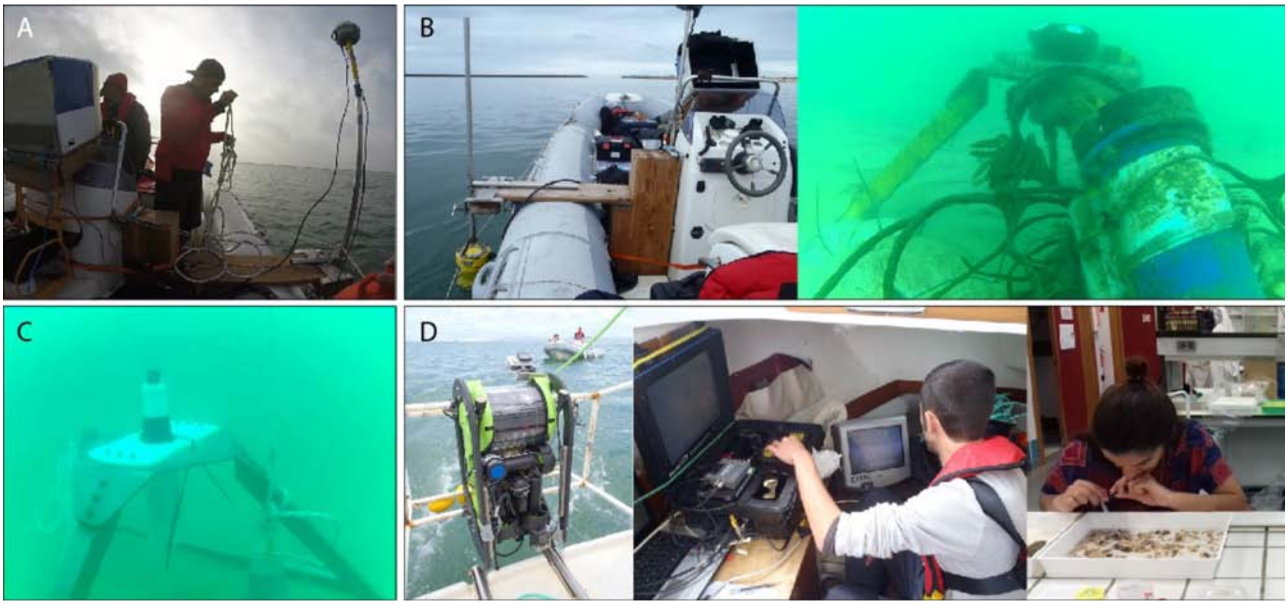

Figure 9.9.
(A) Bathymetric survey using a RTK-DGPS synchronized with the single beam echo-sounder; (B) Characterization of the 3D flow pattern using boat mounted (with bottom tracking) and bottom mounted ADCPs; (C) Acoustic measurements with a hydrophone bottom mounted; and (D) ROV videos and bottom trawling for habitat characterization (adapted from Pacheco et al., 2018).

The SCORE results will assist on validating a model to optimise power extraction having in consideration both the impact and the available resource. A conceptual tidal energy farm will be designed for the pilot site defining the number and appropriate distances between devices of different dimensions. Power generation capacity, energy capture area and proportion of energy flux for the site are the considerations that will be taken into account for the final tidal power plant design. The results can also be used by developers on the licensing process, on overcoming the commercial deployment barriers, on offering extra assurance and confidence to investors, who traditionally have seen environmental concerns as a barrier, and on providing the foundations whereupon similar deployment areas can be considered around the world for marine tidal energy extraction.

Since the project relates to the sustainability of producing electric energy using the Ria Formosa currents, team members are now focused on the cost benefit analysis using as case study the Culatra Island energy demands. This task aims to propose instruments, measures and guidelines that will support the future installation of TEC devices enhancing high levels of environment protection, adapted to real socio-economic scenarios, enabling to define optimum approaches to future tidal energy extraction on coastal estuaries.

A techno-economic assessment will be produced offering: (1) guidelines for device implementation projects on similar coastal lagoons and estuarine systems worldwide analysing scenarios based on energy extraction schemes; (2) a cost benefit analysis on extracting tidal energy from Ria Formosa and adjacent waters. Energy consumptions rates were asked to EDP and different scenarios were established to evaluate project break-even and investment. Installation, operation and maintenance costs are being estimated as well as the possible socio-economic impacts (e.g., job creation, increase of scientific activities related to industry. The work will also quantify the direct and indirect benefits of establishing Ria Formosa as a test case site for testing devices (e.g. local economy, employment), incorporating existing marine renewable energy networks. The tidal energy resource and the evaluation of impacts from extraction at shallow coastal areas proposed on SCORE project can guide energy policy, and position Algarve (and Portugal) on the forefront as test sites for new and/or existing TEC energy developers.

Acknowledgements

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References

DGPM - Direção-Geral de Política do Mar, 2012. Estratégia Nacional para o Mar 2013-2020, 124 p.

EREC - The European Renewable Energy Council, 2010. RE-Thinking 2050: A 100% Renewable Energy Vision for the European Union, 74 p.

European Commission COM 112 final, 2011. A Roadmap for moving to a competitive low carbon economy in 2050, 16 p.

European Ocean Energy, 2013. Industry Vision Paper, 28 p.

EWEA - The European Wind Energy Association, 2014. The European offshore wind industry -key trends and statistics 2013, 22 p.

Fairley, I., Evans, P., Wooldridge, C., Willis, M., Masters, I., 2013. Evaluation of tidal stream resource in a potential array area via direct measurements. *Renewable Energy* 57: 70-78.

IEA - International Energy Agency, 2017. World Energy Outlook 2017, 32 p.

Kadiri, M., Ahmadian, R., Bokelmann-Evans, B., Falconer, R.A., Key, D., 2014. An assessment of the impacts of a tidal renewable energy scheme on the eutrophication potential of the Severn estuary, UK. *Computers & Geosciences* 71:3-10.

Mackie, G., 2008. Development of Evopod tidal stream turbine. In Proc. Int. Conference on Marine Renewable Energy. The Royal Institute of Naval Architects, London.

Martin-Short, R., Hill, J., Kramer, S.C., Avdis, A., Allison, P.A., Piggott, M.D., 2015. Tidal resource extraction in the Pentland Firth, UK: Potential impacts on flow regime and sediment transport in the Inner Sound of Stroma. *Renewable Energy* 76:596-607.

Neill, S.P., Litt, E.J., Couch, S.J., Davis, A.G., 2009. The impact of tidal stream turbines on large-scale sediment dynamics. *Renewable Energy* 34:2803-2812.

Pacheco, A., Ferreira, Ó., Carballo, R., Iglesias, G., 2014. Evaluation of the tidal stream energy production at an inlet channel coupling field data and modelling. *Energy* 71:104-117.

Pacheco, A., Gorbeña, E., Plomaritis, T.A., Garel, E., Gonçalves, J.M.S., Bentes, I., Monteiro, P., Afonso, C.M.L., Oliveira, F., Soares, C., Zabel, F., Sequeira, C., 2018. Deployment characterization of a floatable tidal energy converter on a tidal channel, Ria Formosa, Portugal. *Energy* 158:89-104.

PNAER, 2009. Plano Nacional de Acão para as Energias Renováveis, 144 p.

SI Ocean, 2014. Wave and Tidal Energy Market Deployment Strategy for Europe, 54 p.

UN – United Nations, 2015. United Nations Framework Convention on Climate Change Draft decision -/CP.21. Adoption of the Paris Agreement, 32 p.

World Energy Council, 2016. World Energy Resources – Marine Energy, 79 p.

10. The application of remote sensing for monitoring the Ria Formosa: the sentinel missions

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10.1. Earth observation to monitor Ria Formosa

The Ria Formosa (RF) coastal lagoon (Figure 10.1) is composed of a group of two peninsulas, five barrier islands that are separated by 6 inlets, which enable the exchange of water, sediments, nutrients and other chemicals between the lagoon and the ocean. The RF incorporates important habitats, such as salt marshes, dunes, lagoon marshes and intertidal zones. The RF supports a wide range of human activities, including economic sectors such as fisheries and aquaculture, tourism, ecotourism, navigation and port activities, salt and sediment extraction (Newton et al., 2014). Essentially, these economic activities depend on the ecosystem services of the lagoon including food provisioning (mainly shellfish and fish), hydrological balance, climate regulation, flood protection, water purification, oxygen production, primary and secondary production, recreation and ecotourism (Newton et al., 2018).

Due to its environmental importance, the RF has been a Natural Park since 1987 and is part of the Natura 2000 network. The wetland area is specifically protected under the Ramsar convention.

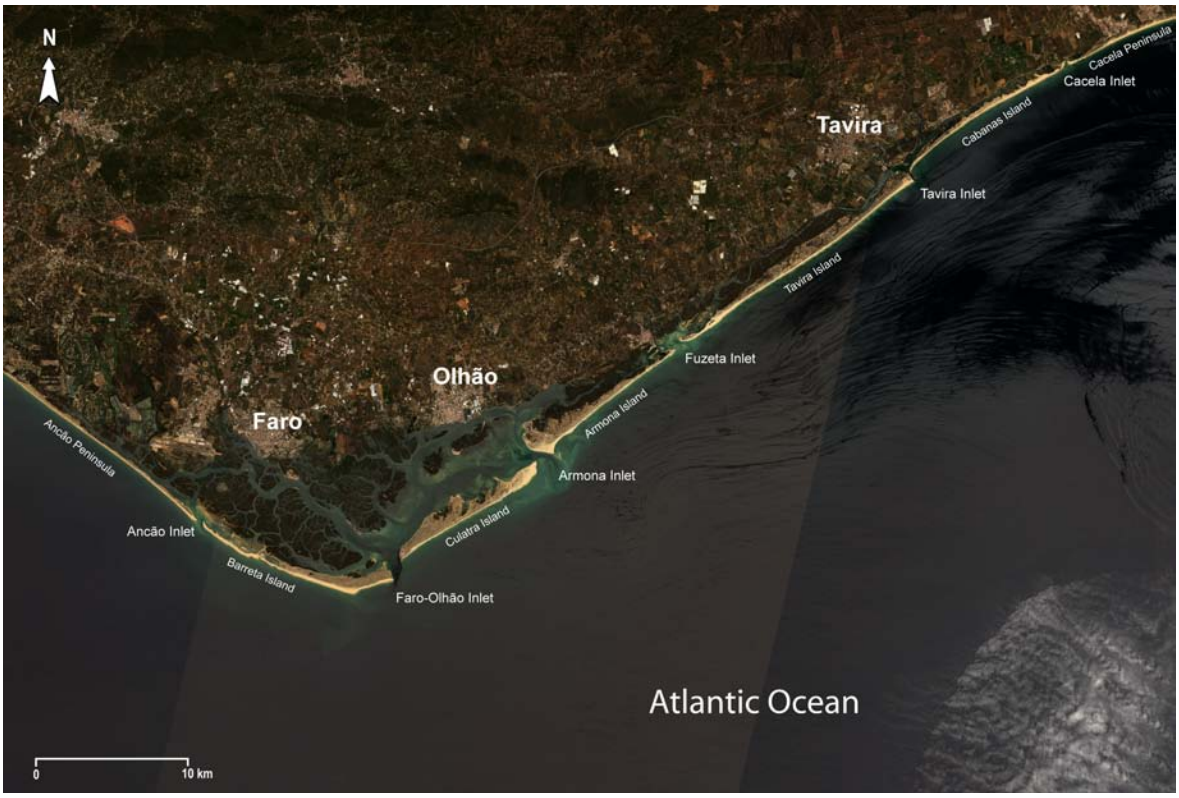


Figure 10.1.
Satellite image on the 20 May 2016 from Sentinel-2 Level-1C showing the Ria Formosa lagoon.

The RF is a vulnerable, complex and dynamic system that is changing constantly due to natural and human influences. Under national and EU laws, there is a legal obligation to provide continuous environmental monitoring of the system, despite the complexity and cost of this obligation. With regard to this monitoring effort, earth observation (EO) from satellites is increasingly considered to be a cost-effective tool for monitoring and assessing environmental systems at a synoptic scale, with a high spatial and temporal resolution (IOCCG, 2014).

In the last decades, a wide variety of satellites have been launched by the space agencies for EO with a broad range of sensors and with different spatial and spectral features that have been providing large volumes of data with applications to the entire globe. Coastal lagoons, such as the RF, located at the interface between the land and the ocean, can benefit from EO by receiving data for all three habitats. Thus, EO could be used to monitor the RF with different spatial, temporal and spectral resolution to include land use and land cover (LULC), the area of surface water and its dynamical changes (tidal exchange), the type of vegetation, soil moisture, sea level, and the water quality properties of the lagoon.

10.2. The Sentinel missions

The European Space Agency (ESA) is developing the Sentinels, a series of EO missions in the frame of the European Copernicus programme previously known as Global Monitoring for Environment and Security (GMES). The objective of the Sentinels missions is to ensure the continuity of observations for monitoring the three earth system domains of atmosphere, water and land (Berger et al., 2012). These satellite missions will provide routine multidisciplinary observations with global coverage by operating a range of instruments with different spectral bands and spatial resolutions. Each Sentinel satellite will monitor different aspects of the EO and are based on a constellation of two satellites in the same orbital plane. The individual satellites are designed to have a seven-year lifetime, although each of them carries consumables onboard allowing a mission extension up to twelve years. Beyond the lifetime of each mission, there are plans for replacing each Sentinel satellite to provide continuity to the missions up to 2030.

In this Chapter, the Sentinel missions that will be presented are Sentinel-1, Sentinel-2 and Sentinel-3 (see Box 10.1). These three missions cover physical, biogeophysical, and biological variables of all global habitats, thus they are of specific importance for understanding and monitoring the dynamics of lagoon systems such as the RF. The technical aspects of these satellites are complex, but it is important to have some knowledge of their potential and their limitations as tools for monitoring the RF lagoon.

Box 10.1. Observing the Earth through Sentinel missions

The Sentinel missions are being developed by ESA for the operational needs of the Copernicus programme. The Sentinel missions are based on a constellation of two satellites with each one carrying a range of technologies, such as radar and multi-spectral imaging instruments for land, ocean and atmospheric monitoring, that provide robust datasets for the Copernicus Services. The website https://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Overview4 summarizes the main features of the Sentinel missions and also provides an image gallery of the Sentinel missions.

The **Sentinel-1** mission supports the C-band Synthetic Aperture Radar (SAR) that operates in a polar-orbit with a 12 day revisit time over land and ocean providing continuous data under all weather conditions, with a high spatial resolution and high temporal frequency of observations (Torres et al., 2012). The mission currently has two satellites, Sentinel-1A launched on 3 April 2014 and Sentinel-1B launched on 25

April 2016 (Torres et al., 2012). The mission will continue to provide C-band SAR data complementing the previous ESA missions with the ERS and ENVISAT satellites by maintaining the key features with improved reliability, repeat visits, geographical coverage and rapid data dissemination, culminating in near-daily coverage over Europe and Canada (Torres et al., 2012).

The **Sentinel-2** mission supports the MutiSpectral Instrument (MSI) that operates in a polar orbit with a 5 day revisit time over land and coastal areas, providing a systematic global acquisition of optical high-resolution multi-spectral imagery. This mission currently has two satellites, Sentinel-2A launched on 22 June 2015 and Sentinel-2B launched on 7 May 2017. This mission will complement the EO satellites of Landsat and SPOT with Sentinel-2 satellites measuring the reflected solar spectral radiances in 13 spectral bands with a 290 km swath and spatial resolutions of 10 m (4 visible and near-infrared bands), 20 m (6 red-edge/ shortwave infrared bands) and 60 m (3 atmospheric correction bands) (Drusch et al., 2012).

Sentinel-2 provides data for services such as risk management, LULC state and changes, forest monitoring, food security/early warning systems, water management, soil protection, urban mapping, and monitoring natural hazards (Drusch et al., 2012).

The **Sentinel-3** mission supports the Synthetic aperture Radar ALtimeter (SRAL), Microwave Radiometer (MWR), the Ocean and Land Colour Instrument (OLCI) and the Sea and Land Surface Temperature Radiometer (SLSTR) that operate in a polar orbit with approximately 3 days revisit time (see Box 10.2). This mission also has two satellites with the launch of Sentinel-3A and Sentinel-3B on the 16 February 2016 and 25 April 2018, respectively. Again, these instruments will complement the historical observations from the ESA ENVISAT satellite to include high-accuracy optical, radar and altimetry data for marine and land services, using both satellites to provide a coverage every 2 days over the global ocean (Donlon et al., 2012). The two main objectives of the mission are topographical observations providing altimeter height measurements over inland water and oceans to provide optical measurements of temperature and colour over the ocean. These measurements are being used to support ocean forecasting systems, as well as environmental and climate monitoring (Donlon et al., 2012).

Box 10.2. The main features of the Sentinel-3 instruments

Sentinel-3 has instruments for topographical observations that combine a SAR Radar Altimeter (SRAL) operating in the Ku-band and C-band, and the Microwave Radiometer (MWR) operating with dual-frequency at 23.8 GHz and 36.5 GHz. These two instruments generate products for use in marine meteorology, ocean-atmosphere gas studies, geophysical studies and operational oceanography. For optical measurements, the Ocean and Land Colour Instrument (OLCI) covers 21 spectral bands within the range 0.4–1 µm, with a 1270 km swath, at a maximum spatial resolution of 300 m. For temperature measurements, Sea and Land Surface Temperature Radiometer (SLSTR) covers 9 spectral bands within the 0.5–12 µm spectral range. There are two additional bands for active fire detection; one with a 1420 km swath and a spatial resolution of 500 m for the visible and near-infrared (VNIR) bands, and the other with a 1 km swath for the thermal infrared (TIR) and fire bands.

10.3. How can Sentinel missions contribute to monitoring the Ria Formosa?

10.3.1. Water Quality

The water quality in the Ria Formosa coastal lagoon is affected by various human-induced and natural processes that are modified rapidly by the daily dynamic changes within the system. These changes can be assessed by satellite remote sensing measurements which provide a tool complementary to *in situ* measurements by extending both the spatial and temporal range of the restricted *in situ* measurements. Satellite remote sensing of ocean colour is based on measurements of the light signal that leaves the water surface and is observed with satellite sensors, as is the case with the OLCI ocean colour sensor onboard the satellites Sentinel-3A and Sentinel-3B. The products acquired by this ocean colour provides geophysical water products including the total suspended matter (TSM), chlorophyll *a* concentration (Chl***a***), coloured dissolved matter absorption coefficient (CDM absorption) also referred to as ADG_443_NN where 443 represents the band wavelength in nm, and NN refers to the originating algorithm, as well as the diffuse attenuation coefficient (Kd), for offshore and coastal applications. These satellite products are used for water quality monitoring programs (Sipelgas et al., 2018) and provide indicators for classification systems of ecological status (Attila et al., 2018). In nearshore coastal and inland waters, the MSI sensor of the Sentinel-2 mission can also provide useful data on the water constituents Chl*a,* TSM, CDM absorption (Pahlevan et al., 2017).

Chl*a* is a *proxy* for phytoplankton biomass that can be used as an indicator to assess eutrophication and to identify the occurrence of algal blooms. The water transparency/clarity reflects the degree that light can penetrate vertically, whereby the water quality can be assessed by the Kd and the TSM. The TSM product represents particulate material, either of organic or mineral origin, that can be transported over long distances within the coastal region. This product, besides giving valuable information about the transparency in the water, can also provide information about the dispersion of sediments that are resuspended by shipping (Sipelgas et al., 2018), dredging operations, or supplied by rivers and erosion (IOCCG, 2008).

Cristina et al. (2015) show examples of how Chl*a* can be used as an indicator to assess the Descriptor 5 for Eutrophication of the Marine Strategy Framework Directive. In this study, Chl*a* has been used to detect and track the development of algal blooms in coastal and marine waters; values of Chl*a* have been extracted from the satellite images along transects perpendicular to the coast to assess the variability of this water product at different distances from the coast; and a time series of Chl*a* concentrations have been used to study the seasonal and interannual variability of this parameter along a timeline. Similar examples can also be provided for the other products acquired by satellite ocean colour remote sensing. Figure 10.2a-d show examples of water products from images of the central part of the Ria Formosa coastal lagoon, provided by the OLCI ocean colour sensor. In addition to the TSM and CDM absorption products, there is a comparison between the two algorithms, CHL_OC4Me and the CHL_NN, that derive chlorophyll concentration for Case 1 and Case 2 waters, respectively (Box 10.3).

Box 10.3. What are Case 1 and Case 2 waters?

Case 1 refers to open ocean waters, where the dominant components affecting the contribution of absorption and spectral backscattering to the optical properties of the open ocean, are the water itself and the phytoplankton. The optical contribution from coloured dissolved matter absorption coefficient (CDM absorption) and total suspended matter (TSM) are assumed to be small compared to chlorophyll a (Chl*a*). Thus, the development of algorithms for retrieving phytoplankton pigments from remotely sensed ocean colour can be modelled solely as a function of the Chl*a* concentration.

In contrast, Case 2 waters include inland and coastal waters where the contribution of CDM absorption and TSM to the optical properties are high. These waters are optically more complex requiring the development of algorithms that include an atmospheric correction and retrievals of ocean bio-optical properties from water leaving reflectances.

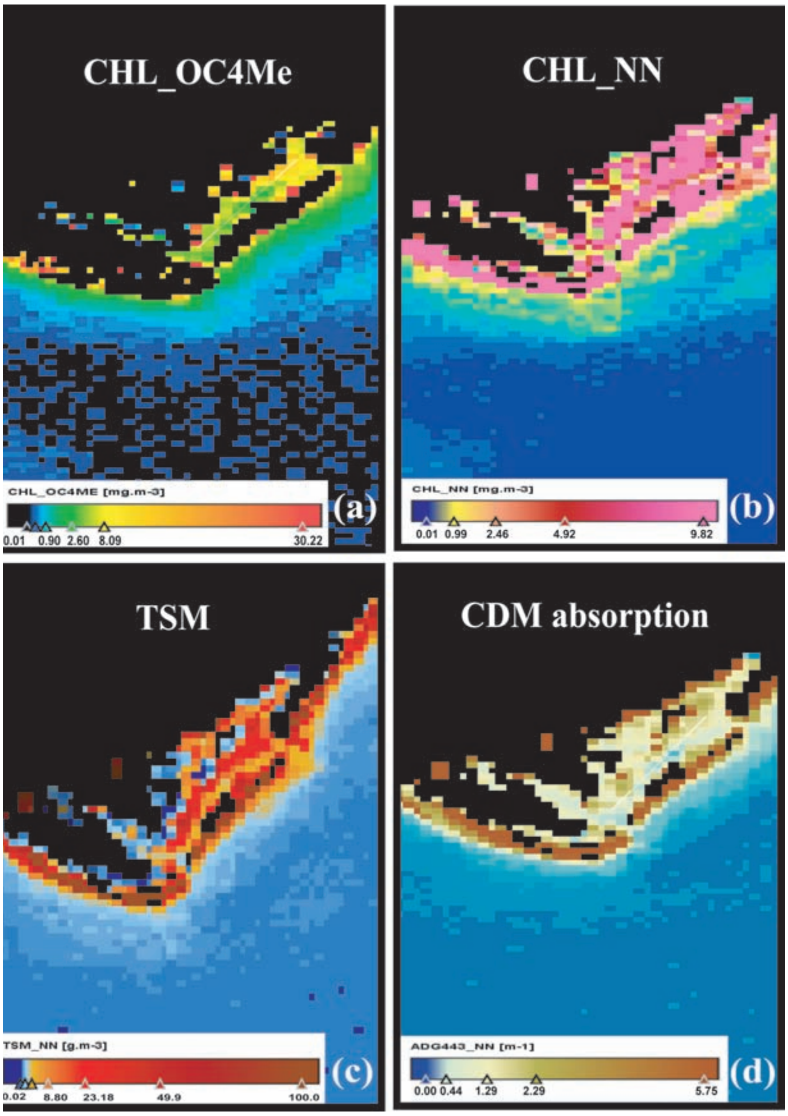


Figure 10.2.
Satellite image on the 16 November 2017 from the OLCI ocean colour sensor of Sentinel-3A showing the central section of the Ria Formosa. The different water products derived from the image include: **(a)** chlorophyll from the CHL_OC4Me algorithm, **(b)** chlorophyll from the CHL_NN algorithm, **(c)** total suspended matter (TSM) and **(d)** coloured dissolved matter absorption coefficient (CDM absorption).

10.3.2. Wetlands

Wetlands are essential ecosystems for maintaining and improving water quality, mitigating floods, providing habitat for fish and wildlife, preventing floods, protecting coastlines from breaching tidal waters and providing a site for carbon sequestration (Whyte et al., 2018). However, due to increased pressure caused by an urban expansion, changes in land use and, also, changes induced by climate change in these ecosystems, it is important to track how these pressures may impact wetlands (Whyte et al., 2018).

As has been shown earlier in this Chapter, the RF is a Ramsar site where there is a continuous effort to understand how the natural and anthropogenic changes are affecting the wetland. There is increasing recognition that satellite remote sensing can provide maps at regular intervals on the distribution between open water bodies, and vegetation cover within the lagoon (Fig 10.3a-c). Indeed, the studies by Whyte et al. (2018) and Chatziantoniou et al. (2017) have shown how the synergy of the Sentinel-1 and -2 missions can complement each other for monitoring wetlands. Sentinel-1's radar data can track the presence of partially submerged vegetation, while the optical data of Sentinel-2, can highlight areas covered in vegetation at low tide. Using the capabilities of SAR imagery, Sentinel-1 can effectively map the inundation level, biomass and soil moisture of wetlands (Chatziantoniou et al., 2017). Sentinel-2 has a wide range of high-resolution spectral bands that can provide the Normalized Difference Vegetation

Index (NDVI) (Figure 10.3b) and the Normalized Difference Water Index (NDWI) (Figure 10.3c) to help discriminate between surface water and vegetation types (see Box 10.4).
Figure 10.4 shows an example of a Sentinel-1A image where wetland area within the RF lagoon can be observed.

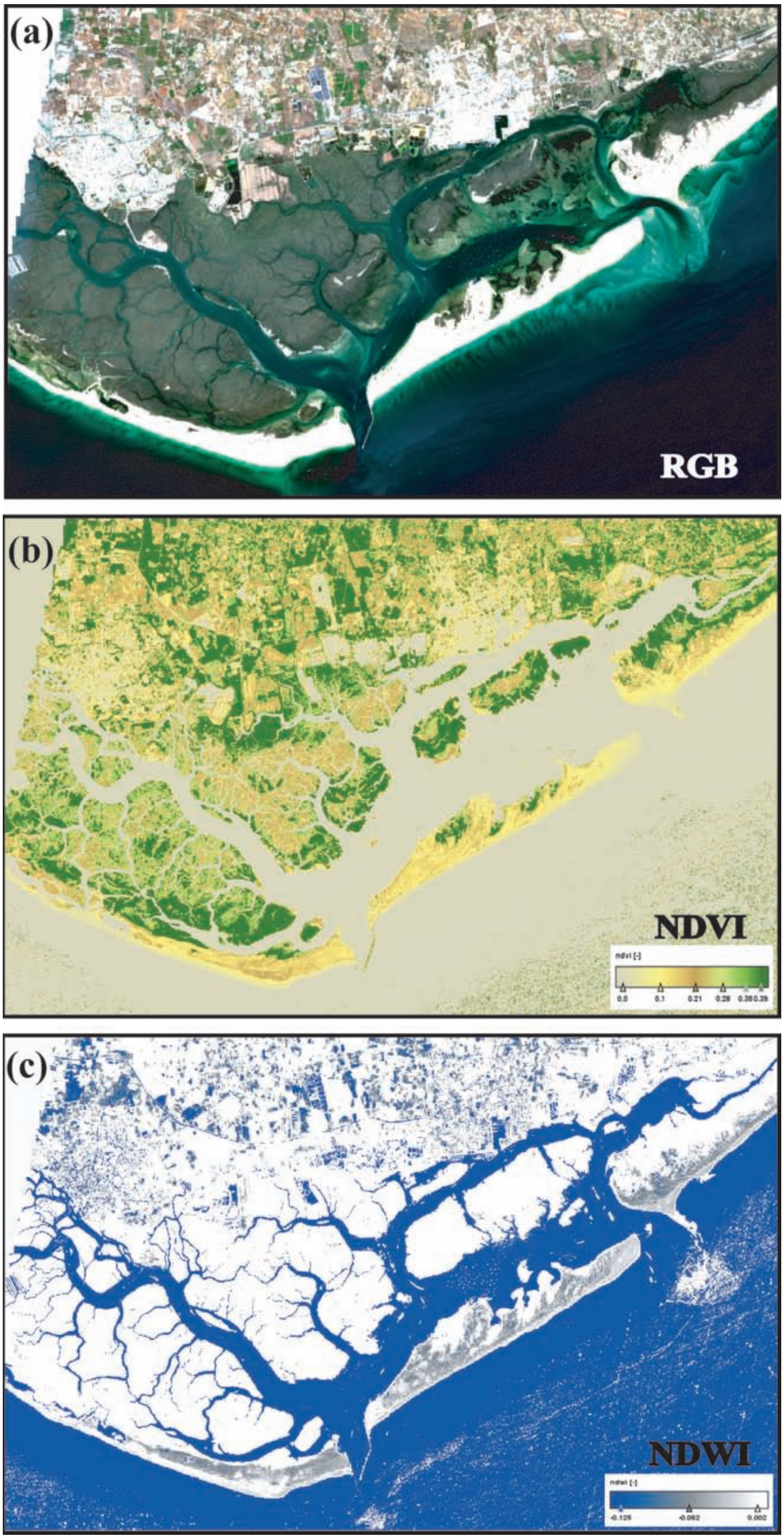


Figure 10.3.
Sentinel-2A MSI Level 2 image of the Ria Formosa on 6 of July 2018 where **(a)** is the RGB image which has been processed in **(b)** with the vegetation radiometric index (NDVI-Normalized Difference Vegetation Index), where the value between -1 (beige colour) correspond to water and the values approaching 1 (dark green colour) indicate the high vegetated areas, and in **(c)** with the water radiometric index (NDWI-Normalized Difference Water Index), where the zero values are assumed to represent aquatic surfaces (blue colour), while values less than, or equal to zero, are assumed to be terrestrial surfaces (white colour).

Box 10.4. What are NDVI and NDWI indices?

The Normalized Difference Vegetation Index (NDVI) is the standard index for comparing vegetated with non-vegetated areas in wetlands. It normalizes green leaf scattering in the near infra-red wavelength and chlorophyll absorption in the red wavelength. NDVI ranges in value between -1 (beige colour) to 1 (dark green colour) where: the negative values correspond to water; the positive values between 0.1 and 0.2 represent barren areas of rock, sand, or snow; positive values between 0.2 and 0.4 represent shrub and grassland; and high values approaching 1 indicate temperate and tropical rainforests.
The Normalized Difference Water Index (NDWI) is appropriate for mapping the presence of surface waters in wetland environments and allows for estimations of cover by surface waters; where water bodies show strong absorption and low radiation in the range from visible to infrared wavelengths. Based on this phenomenon, this index uses the green and near infra-red bands of remote sensing images, where the values of NDWI greater than zero are assumed to represent aquatic surfaces (blue colour), while values less than, or equal to zero, are assumed to be terrestrial surfaces (white colour).

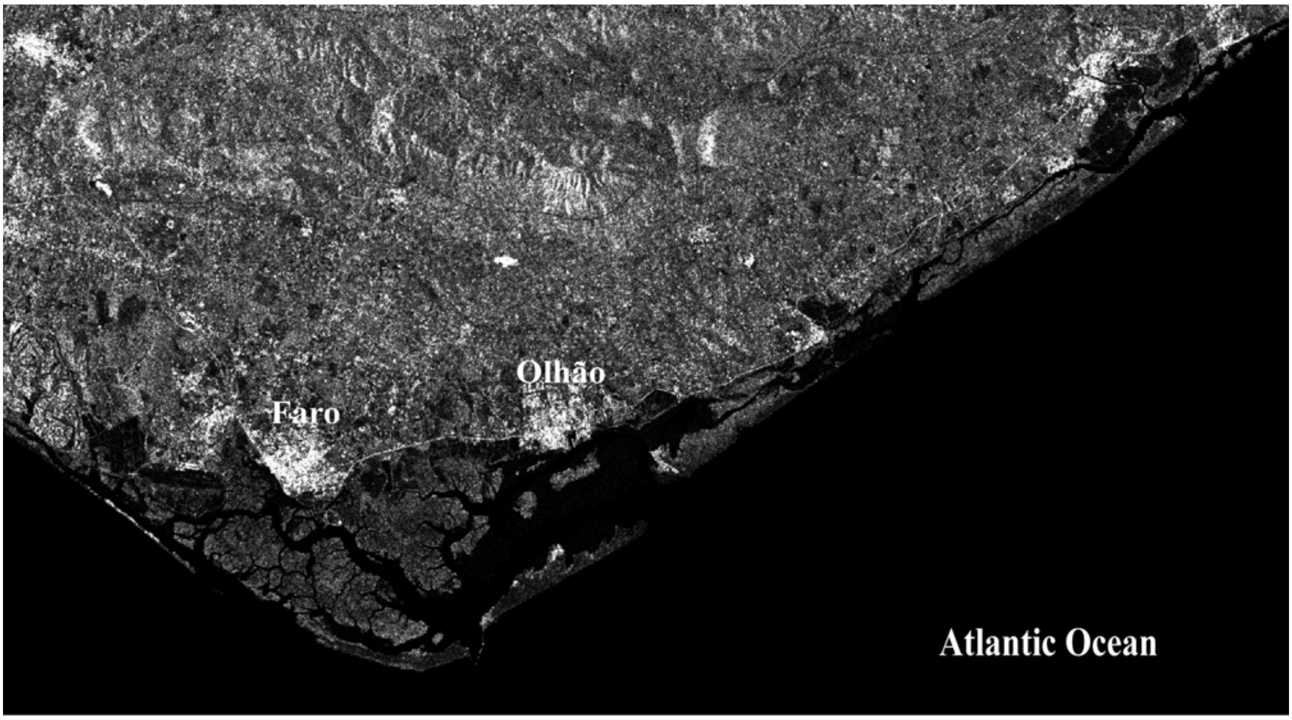


Figure 10.4.
Sentinel-1A satellite image of the Ria Formosa on 14 July 2018.

10.3.3. Shoreline monitoring

The Ria Formosa shoreline extends over 55 km and consists of beaches and dune systems that occupy 13% of the total system surface (Plomaritis et al., 2018). Although this shoreline has high ecological, economic, and social importance, it is exposed to overwash, waves, winds, nearshore currents, erosion (Plomaritis et al., 2018). Monitoring the natural and anthropogenic pressures on this highly dynamic shoreline requires the use of appropriate scales in time and space. Assessment of shoreline changes include *in situ* beach profiling, maps, aerial photography, unmanned aerial vehicles such as drones, and light detection and ranging surveys (LIDAR), although these tools are limited to studying the trends and seasonal changes along time and space and are often expensive (García-Rubio et al., 2015). The use of satellite remote sensing provides EO data that overcome these limitations providing time series that show the evolution of the shoreline and its dynamics along time and at different scales. Several studies have used satellite images to monitor the shoreline; for example, Hagenaars et al. (2018) show the use of Sentinel-2 to detect the Satellite Derived Shoreline position from satellite imagery and test its accuracy.

10.3.4. Ecosystems services

Wetland, salt-marsh, and seagrass habitats are essential habitats for bivalves, crustaceans, fish and birds that contribute to a high biodiversity supporting valuable ecosystem services with important ecological, economic, and social benefits (Newton et al., 2018). The ecosystem services of the RF include food provisioning, hydrological balance, climate regulation, flood protection, water purification, oxygen production, primary and secondary production, recreation and ecotourism, all contributing to the livelihoods, wellbeing and welfare of humans (Newton et al., 2018). However, this system is vulnerable to unfavourable impacts on the ecosystem services from natural or anthropogenic changes. The application of EO provides essential information on the functioning of ecosystems and on the drivers of environmental change and can complement the socioeconomic information and model-based analysis that are used to assess the supply, demand, and benefit of ecosystem services (Cord et al., 2017). Ecosystem functions are more readily evaluated by EO than the demand and benefit of the ecosystem services. The difference is that ecosystem functions are controlled by abiotic and climatic factors, ecosystem structure, biodiversity and human impacts, whilst ecosystem services describe the benefits that humans receive from those ecosystem functions (Cord et al., 2017).

Nonetheless, the radar (Sentinel-1) and optical (Sentinel-2 and Sentinel-3) data provided by these satellite missions can be used in different ways to evaluate and analyse the ecosystem services provided by the RF. One of the main ecosystems services of the RF is the food provisioning that is responsible for 90% of the national production of bivalve shellfish (clams, oysters and mussels) in Portugal. Clearly, evaluating changes in the aquaculture activities of the RF is essential for the regional economy. Mapping the location of aquaculture activities is an important first stage; for example, the site for an oyster farm in Moinho dos Ilhéus is shown in the Sentinel 2 satellite image from the Eastern region of the RF in Figure 10.5. As bivalve shellfish are filter feeders, the availability of phytoplankton for food and good water quality are essential components for the success of this aquaculture. Thus, the water products provided through Sentinel-2 and Sentinel-3 (see Section 10.3.1) are useful for monitoring conditions available for aquaculture in the RF. For example, the concentration of Chl*a* can be used as a proxy for phytoplanktonic biomass and as an indicator of algal blooms.

The human settlement and population density around this lagoon also can affect the water quality resulting in impacts on food provisioning as well as other ecosystem services of the RF such as recreation and ecotourism. Monitoring human settlement through time can be made using Sentinel-2 data by mapping the LULC and relating these maps to other EO products affecting the ecosystem services of the RF.

Figure 10.5.
Sentinel-2A MSI Level 2 image of the east section of the Ria Formosa on 6 July 2018 showing the location of an oyster aquaculture facility (black square).

Ecotourism is a recent economic activity that has been expanding in the RF. This activity could be considered an example of how humans can sustainably obtain economic benefits from nature, using the profit to contribute to the regional economy. The number of ecotourism companies that operate inside the lagoon has increased in the last decade and it offers the possibility to visit barrier islands, lagoon channels, marine life observation, bird watching and hiking. The expansion of this activity can be readily monitored with high-resolution satellite images to identify the recreational infrastructure and facilities, supporting this activity such as ramps for launching boats and the development of paths and benches for hiking activities (Cord et al., 2017). As with other touristic, recreational and leisure activities, EO can be used to provide readily available information about the state of the ecosystem for clients.
Figure 10.6 shows a satellite image where it is possible to map different economic activities in the RF based on locating various facilities within and around the lagoon including areas for sailing, fisheries and is also identifying the traffic of boats during the high tourism season in the lagoon system between the city of Olhão and the Culatra and Armona Islands.

Figure 10.6.
Satellite image on 06 July 2018 from Sentinel-2A MSI Level 2 showing locations in the Ria Formosa at Olhão for sailing (1) and fisheries (2), as well as landing facilities on the barrier island of Culatra (3).

In summary, these are some examples of how EO data can be used to estimate the ecosystems services of the RF. However, it is evident that the EO data should complement socio-economic information and model-based analysis to support the assessment of the ecosystem services supply, demand, and benefit (Cord et al., 2017).

10.4. The limitations of the use of earth observations

The use of EO to assess and monitor the RF is a powerful tool to manage and protect this extremely dynamic system by providing suitable local and regional information about their status and trends However, these are complex systems that are influenced by both the land and the ocean at the interface between these two systems. Typically, in terms of EU legislation such as the European Water Framework Directive (WFD) the RF could be considered a transitional water, but in fact, the RF shares more characteristics with coastal waters with limited input of freshwater and an extensive exchange through its inlets with the fully saline water of the Atlantic Ocean. The earlier sections of this Chapter have provided examples of how EO can contribute to the management of this shallow, dynamic coastal lagoon, but it is also important to know the limitations of EO. It is evident that specific satellite missions show differences in spatial and temporal coverage, spatial resolution, revisit frequency, and spectral coverage; some of these differences which will be more relevant than others for effective coastal management strategies. In comparison with ocean conditions, the RF shows many processes that can occur more rapidly and at smaller scales than in the ocean such as, nearshore tidal currents, resuspension of sediments, point-source delivery of nutrients, and highly dynamic algal blooms. It is evident that only satellite images with higher resolutions can capture these processes in spatially heterogeneous water bodies (Mouw et al., 2015). With regard to the RF, the higher spatial resolution of Sentinel-2 has advantages relative to other satellite missions. However, there are other disadvantages to the polar orbiting Sentinels in that their revisit time may be insufficient to obtain information about short-term changes in water properties. Rapid changes occurring over a few hours can be best characterized by high-frequency measurements from geostationary platforms (Mouw et al., 2015). Other limitations for optical satellite missions are cloud cover that will constrain the use of optical products, bottom reflectance, the impact of the atmospheric correction and adjacency effects that contaminate the spectral remote sensing reflectances data that are used in bio-optical algorithms to retrieve quantitative in-water, optical, biogeochemical and water quality information. It is important to validate the satellite products with *in situ* measurements to improve the global algorithms that are developed to retrieve the EO products and that can also be used to develop regional algorithms, with specific application for coastal lagoons. Figure 10.7 show a transect of Chl*a* concentration between the Faro-Olhão inlet and the Armona Inlet where the two algorithms to derive this product was extracted from the Sentinel-3A/OLCI on 16 November 2017. The higher concentrations of Chl*a* occur at the two extremes of the transects closer to the inlets where this data can be contaminated with the bottom reflectance in these shallow areas. In contrast, the central section of the transect has a deeper channel which is less affected by bottom reflectance. This is an example of why it is important that satellite data in coastal lagoons must be validated with *in situ* measurements to assess which are the most appropriate algorithms for use in these lagoon waters.

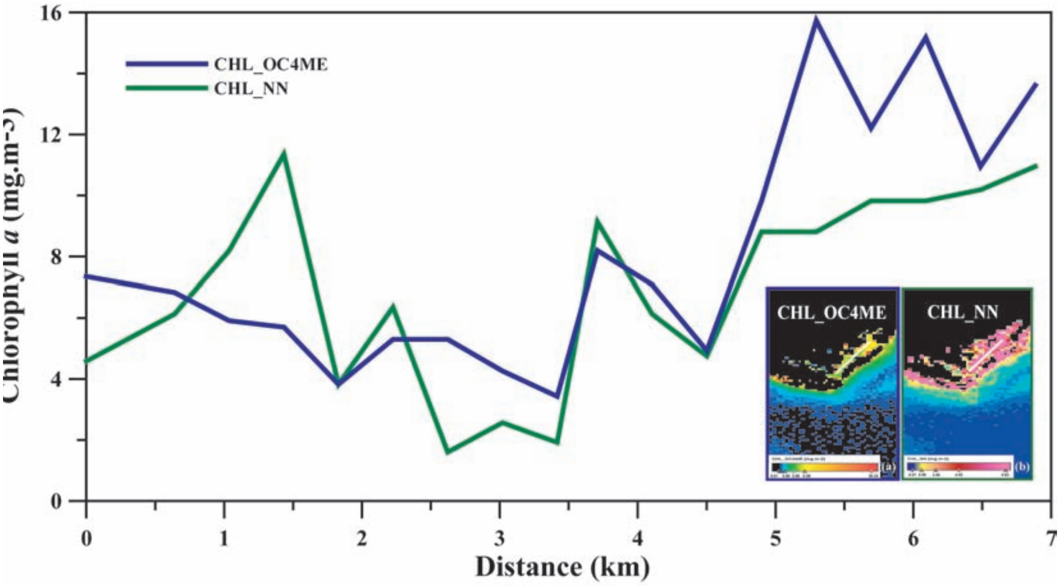


Figure 10.7.
Sentinel-3A OLCI transects, extending from Faro-Olhão to Armona Inlet of the Ria Formosa on 16 November 2017, comparing chlorophyll *a* concentrations retrieved by the algorithms CHL_OC4Me (blue line) and CHL_NN (green line). The transects have been extracted from the Sentinel-3A OLCI satellite images ((a) for the CHL_OC4Me and (b) for the CHL_NN) and are represented by the white line in the images of the lagoon.

Comparison of EO products under different tidal conditions of the Ria Formosa is an additional problem for interpreting satellite images at different stages of the tide. At low tide, the volume of water in the channels is sufficiently reduced that images from Sentinel 3 mask the water as land even if they are at the full resolution of 300 m. Figure 10.8 compares two OLCI images form Sentinel 3 under different tidal conditions. In addition to the masking effect at low tide, there is an additional masking at the extremes of the lagoon where the water channels are smaller and narrower than the wider channels at the centre of the lagoon. Again, these smaller channels are interpreted as land by the processing algorithm.

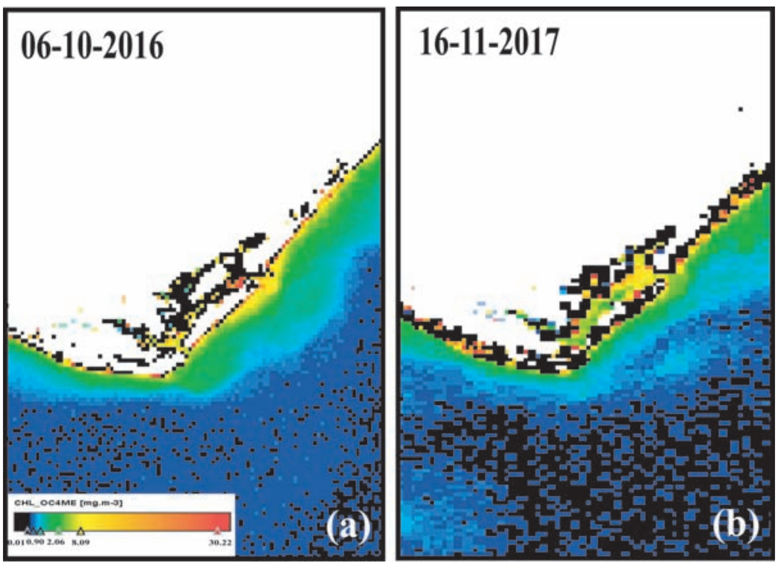


Figure 10.8.
Sentinel-3A OLCI CHL_OC4Me algorithm when the Ria Formosa is at low tide (a) and between low and high tide condition (b), where the white pixels represent the land, respectively on 6th October 2016 and on 16th November 2017.

In contrast to the optical missions, satellite missions that provide radar data can supply data in all-weather conditions and at all stages of the day and night which has considerable advantages when monitoring a

highly dynamic system such as the RF. However, there are some limitation that must be taken into consideration when using satellite radar altimetry in coastal lagoons including the land contamination in the footprint that impacts the radar echo, the shallow water, and the reduced quality of the corrections applied to the distance between the satellite and the ocean/land surface (Salameh et al., 2018). Consequently, the accuracy of the measurements taken by radar satellite missions decreases in the direction towards coastal areas where the noise in the satellite radar images is higher. Increasing the accuracy of the radar data will benefit from continuing improvements to the processing and screening of altimetric data as well as geophysical corrections to include wet tropospheric, tidal and dynamical atmospheric corrections (Salameh et al., 2018).
Using the optical and radar images from Sentinel satellites in synergy, the shortcomings of images from one sensor can be reduced by using images from other sensors with different characteristics.
Indeed, the management of the RF lagoon would benefit from a coherent package of procedures of which EO would be part.

References

Attila, J., Kauppila, P., Kallio, K.Y., Alasalmi, H., Keto, V., Bruun, E. & Koponen, S., 2018. Applicability of Earth Observation chlorophyll-a data in assessment of water status via MERIS — With implications for the use of OLCI sensors. *Remote Sensing of Environment* 212:273–287.

Berger, M., Moreno, J., Johannessen, J.A., Levelt, P.F. & Hanssen, R.F., 2012. ESA's Sentinel missions in support of Earth system science. *Remote Sensing of Environment* 120:84–90.

Chatziantoniou, A., Petropoulos, G.P. & Psomiadis, E., 2017. Co-orbital Sentinel 1 and 2 for LULC mapping with emphasis on wetlands in a Mediterranean setting based on machine learning. *Remote Sensing* 9: 1259, doi:10.3390/rs9121259.

Cord, A. F., Brauman, K. A., Chaplin-Kramer, R., Huth, A., Ziv, G. & Seppelt, R., 2017. Priorities to advance monitoring of ecosystem services using earth observation. *Trends in Ecology & Evolution* 32: 416-428.

Cristina, S., Icely, J., Goela, P.C., DelValls, T.A. & Newton, A., 2015. Using remote sensing as a support to the implementation of the European Marine Strategy Framework Directive in SW Portugal. *Continental Shelf Research* 108:169-177.

Donlon, C., Berruti, B., Buongiorno, A., Ferreira, M.-H., Féménias, P., Frerick, J., Goryl, P., Klein, U., Laur, H., Mavrocordatos, C., Nieke, J., Rebhan, H., Seitz, B., Stroede, J. & Sciarra, R., 2012. The Global Monitoring for Environment and Security (GMES) Sentinel-3 mission. *Remote Sensing of Environment* 120:37–57.

Drusch, M., Del Bello, U., Carlier, S., Colin, O., Fernandez, V., Gascon, F., Hoersch, B., Isola, C., Laberinti, P., Martimort, P., Meygret, A., Spoto, F., Sy, O., Marchese, F. & Bargellini, P., 2012. Sentinel-2: ESA's optical high-resolution mission for GMES operational services. *Remote Sensing of Environment* 120: 25–36.

García-Rubio, G., Huntley, D. & Russell, P., 2015. Evaluating shoreline identification using optical satellite images. *Marine Geology* 359:96–105.

Hagenaars, G., de Vries, S., Luijendijk, A.P., de Boer, W. P. & Reniers, A.J.H.M., 2018. On the accuracy of automated shoreline detection derived from satellite imagery: A case study of the sand motor mega-scale nourishment. *Coastal Engineering* 133:113–125.

IOCCG, 2008. Why Ocean Colour? The Societal Benefits of Ocean-Colour Technology. Platt, T., Hoepffner, N., Stuart, V. and Brown, C. (Eds.), Reports of the International Ocean-Colour Coordinating Group, No. 7, IOCCG, Dartmouth, Canada, 141p.

IOCCG, 2014. Phytoplankton Functional Types from Space. Sathyendranath, S. (Ed.), Reports of the International Ocean-Colour Coordinating Group, No. 15, IOCCG, Dartmouth, Canada, 156 p.

Mouw, C.B., Greb, S., Aurin, D., DiGiacomo, P.M., Lee, Z., Twardowski, M., Binding, C., Hu, C., Ma, R., Moore, T., Moses, W. & Craig, S.E., 2015. Aquatic color radiometry remote sensing of coastal and inland waters:

Challenges and recommendations for future satellite missions. *Remote Sensing of Environment* 160:15–30.

Newton. A., Icely, J.D., Cristina, S., Brito, A., Cardoso, A. C., Colijn, F., Riva, S.D., Gertz, F., Hansen, J.W., Holmer, M., Ivanova, K., Leppakoski, E., Canu, D.M., Mocenni, C., Mudge, S., Murray, N., Pejrup, M., Razinkovas, S., Reizopoulou, S., Pérez-Ruzafa, A., Schernewski, G., Schuber, H., Carr, L. C., Solidoro, C., Viaroli, P. & Zaldívar, J.M., 2014. An overview of ecological status, vulnerability and future perspectives of European large shallow, semi-enclosed coastal systems, lagoons and transitional waters. *Estuarine, Coastal and Shelf Science* 140: 95-122.

Newton, A., Brito, A.C., Icely, J.D., Derolez, V. Clara, I., Angus, S., Schernewski, G., Inácio, M., Lillebø, A.I., Sousa, A.I., Béjaoui, B., Solidoro, C., Tosic. M., Cañedo-Argüelles, M., Yamamuro, M., Reizopoulou, S., Tseng, H-C., Donata, C., Roselli, L., Maanan, M., Cristina, S., Ruiz-Fernández, A.C., Lima, R., Kjerfve, B., Rubio-Cisneros, N., Ruzafa, A.P., Marcos, C., Pastres, R., Pranovi, F., Snoussi, M., Turpie, J., Tuchkovenko, Y., Dyack, B., Brookes, J., Povilanskas, R. & Khokhlov, V., 2018. Assessing, quantifying and valuing the ecosystem services of coastal lagoons. *Journal for Nature Conservation* 40:50-65.

Pahlevan, N., Sarkar, S., Franz, B.A., Balasubramanian, S.V. & He, J., 2017. Sentinel-2 MultiSpectral Instrument (MSI) data processing for aquatic science applications: Demonstrations and validations. *Remote Sensing of Environment* 201:47–56.

Plomaritis, T.A., Costas, S. & Ferreira, O., 2018. Use of a Bayesian Network for coastal hazards, impact and disaster risk reduction assessment at a coastal barrier (Ria Formosa, Portugal). *Coastal Engineering* 134:134–147.

Torres, R., Snoeij, P., Geudtner, D., Bibby, D., Davidson, M., Attema, E., Potin, P., Rommen, B., Floury, N., Brown, M., Traver, I.N., Deghaye, P., Duesmann, B., Rosich, B., Miranda, N., Bruno, C., L'Abbate, M., Croci, R., Pietropaolo, A., Huchler, M. & Rostan, F., 2012. GMES Sentinel-1 mission. *Remote Sensing of Environment* 120:9–24.

Salameh, E., Frappart, F., Marieu, V., Spodar, A., Parisot, J-P., Hanquiez, V., Turki, I., & Laignel, B., 2018. Monitoring sea level and topography of coastal lagoons using satellite radar altimetry: The example of the Arcachon Bay in the Bay of Biscay. *Remote Sensing* 10(2), 297.

Sipelgas, L., Uiboupin, R., Arikas, A. & Siitam L., 2018. Water quality near Estonian harbours in the Baltic Sea as observed from entire MERIS full resolution archive. *Marine Pollution Bulletin* 126:565–574.

Whyte, A., Ferentinos, K.P. & Petropoulos G.P., 2018. A new synergistic approach for monitoring wetlands using Sentinels-1 and 2 data with object-based machine learning algorithms. *Environmental Modelling & Software* 104:40-54.

GLOSSARY

ABIOTIC FACTORS: in biology and ecology, abiotic components or abiotic factors are non-living chemical and physical parts of the environment that affect living organisms and the functioning of ecosystems.

ABSORPTION: is any process whereby radiant energy is converted to non-radiant energy, e.g., to thermal, chemical, vibrational, or rotational energy of a molecule. Absorption results in the loss of photons.

ACTIVATED SLUDGE: is a type of wastewater treatment process for treating sewage or industrial wastewaters using aeration and a biological floc composed of bacteria and protozoa. The process takes advantage of aerobic micro-organisms that can digest organic matter in sewage, and clump together (by flocculation) as they do so. It thereby produces a liquid that is relatively free from suspended solids and organic material, and flocculated particles that will readily settle out and can be removed.

ADCP- ACOUSTIC DOPPLER CURRENT PROFILER: equipment used to measure current velocities using the Doppler effect i.e. the echo of the sound on particles of water, assuming that the particles move on 3D directions at the same velocity of the water.

ADIPOSE TISSUES: body fat.

ADSORPTION: the formation of a thin layer of a substance that is held on the surface of a solid due to a combination of weak physical and chemical forces.

AERENCHYMA SYSTEM: is a spongy tissue that forms spaces or air channels in the leaves, stems and roots of some plants, which allows exchange of gases between the shoot and the root.

ALONGSHORE DRIFT: transport of sediment parallel to the shoreline.

ANOXIA: waters devoid of dissolved oxygen.

ASH-FREE DRY WEIGHT (AFDW): is a measurement of the weight of organic material. In order to measure AFDW, the first step is to remove all water by drying at a low temperature (around 60 °C). The resulting dry weight is the weight of both the organic and inorganic contents of the sample. Next, the dried sample is combusted by placing the sample in an oven (around 450 °C). The ash that is left over is thus the inorganic contents of the sample. The AFDW is then the dry weight (inorganic + organic contents) minus the weight of the ash (inorganic contents only). AFDW is therefore the weight of the organic content of the sample.

AUTOTROPHS: organisms capable of fixing CO_2 into organic compounds or biomass.

BACKBARRIER: is a narrow, elongate, intertidal, sloping landform that is usually parallel to the shoreline located on the lagoon or estuary side of the barrier island, or spit.

BACTERIAL MINERALIZATION: Refers to the processes by which bacteria make inorganic minerals, from decaying organic matter present in the environment.

BENTHIC HABITATS: are the ecological regions at the lowest level of aquatic ecosystems such, including the sediment surface and some sub-surface layers. Organisms living in these zones are called benthos.

BENZENE RINGS: a structural arrangement of atoms in benzene and other aromatic compounds that consists of a planar, symmetrical hexagon of six carbon atoms.

BERN CONVENTION: is a binding international legal instrument in the field of nature conservation, covering most of the natural heritage of the European continent and extending to some states in Africa. It aims to conserve wild flora and fauna and their natural habitats, as well as to promote European co-operation in this field. The treaty also takes account of the impact that other policies may have on natural heritage and recognises the intrinsic value of wild flora and fauna, which needs to be preserved and passed to future generations.

BIOACCUMULATION: the accumulation of a substance in a biological organism usually due to its lipophilicity.

BIOAVAILABILITY: a measure of the ease by which various substances in the environment may enter into living organisms.

BIOCHEMICAL OXYGEN DEMAND (BOD): this measurement indicates the ability of micro-organisms to metabolize an organic substance in the presence of oxygen and therefore the potential for depletion of oxygen by this organic substance.

BIODIVERSITY: means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part. This includes diversity within species, between species and of ecosystems.

BIOGEOCHEMICAL PROCESSES: relating to or denoting the cycle in which chemical elements and simple substances are transferred between living systems and the environment.

BIOINDICATOR: a living organism that gives us a measure of the health of an ecosystem.

BIOMARKER: biological response to a chemical at the individual level or below, demonstrating a departure from normal status. Usually restricted to responses at the level of organization of a whole organism or below.

BIOMASS: is the mass of living biological organisms in a given area or ecosystem at a given time. Biomass can refer to species biomass, which is the mass of one or more species, or to community biomass, which is the mass of all species in the community. It can include microorganisms, plants or animals.

BIOTA: animal and plant life of a particular region, habitat, or geological period.

BIOTURBATION: biogenic transport of sediment particles and pore water which destroys sediment stratigraphy, alters chemical profiles, changes rates of chemical reactions and sediment-water exchange, and modifies sediment physical properties such as grain size, porosity, and permeability.

BOD - BIOCHEMICAL OXYGEN DEMAND: is the amount of dissolved oxygen needed (i.e. demanded) by aerobic biological organisms to break down organic material present in a given water sample at certain temperature over a specific time period.

BOTTOM REFLECTANCE: is light reflected off the bottom of a water body that influence ocean colour.

CATALYTIC CENTRES: the region of an enzyme where substrate molecules bind and undergo a chemical reaction.

CATION EXCHANGE CAPACITY: is a measure of how many cations (positive ions) can be retained on sediment particle surfaces, and affects many aspects of sediments chemistry.

C-BAND: refers to the portion of the electromagnetic spectrum allotted for satellite transmissions in the 4 GHz to 8 GHz frequency range.

CENTRIFUGAL DEWATERING: centrifugal thickening and dewatering of sewage sludge is a high speed process that uses the force from rapid rotation of a cylindrical bowl to separate wastewater solids from liquid.

CFU: in microbiology, a colony-forming unit is a unit used to estimate the number of viable bacteria or fungal cells in a sample. Viable is defined as the ability to multiply via binary fission under the controlled conditions.

CHL_NN ALGORITHM: is chlorophyll concentration calculated according to the Case2R algorithm.

CHL_OC4ME ALGORITHM: is chlorophyll concentration calculated according to the OC4Me MAXIMUM BAND RATIO (MBR) semi-analytical algorithm.

CHLOROPHYLL: is a chemical compound occurring in plants that enable radiant energy to be converted to chemical energy in the process of photosynthesis; there are several types denoted as Chla, Chlb, etc., with Chla typically the most abundant and often used as a proxy for phytoplankton biomass.

CHLOROPHYLL A: is a specific form of chlorophyll used in photosynthesis. It absorbs most energy from wavelengths of violet-blue and orange-red light. It also reflects green-yellow light, and as such contributes to the observed green colour of most plants.

CHLOROPLASTS: chlorophyll containing organelles where photosynthesis takes place.

CHROOCOCCOID: rounded bacteria possessing photopigments.

CILIATES: protozoan class (Ciliata) characterized by having cilia used for locomotion and prey capture; voracious grazers of bacteria and micro-algae.

CLOUD COVER: is the fraction of the sky obscured by clouds when observed from a particular location.

COD - CHEMICAL OXYGEN DEMAND: is an indicative measure of the amount of oxygen that can be consumed by reactions in a measured solution. It is commonly expressed in mass of oxygen consumed over volume of solution which in SI units is milligrams per litre (mg/L).

COLOURED DISSOLVED MATTER ABSORPTION COEFFICIENT: is the absorption of coloured detrital and dissolved material at 443 nm.

CORDGRASS: is the common name of the plants of *Spartina* genus, in the grass family frequently found in coastal salt marshes.

CYANOBACTERIA BLOOMS: rapid growth of cyanobacteria attaining abundances above a threshold value (> 1.5 x 106 cells. L^{-1}).

CYANOBACTERIA: photosynthetic prokaryotes containing chlorophyll a and phycobilin proteins as accessory pigments.

CYTOPLASM: organic matrix or gel-like substance inside cells.

DAPI: 4 ,6-diamidino-2-phenylindole fluorescent stain that binds strongly to adenine–thymine rich regions of nucleic acids (DNA).

DECHLORONIZATION: water treatment process used to decrease the concentration of chlorine atoms or chloride ions in water.

DEGRADATION: the condition or process of spoiling or destroying the beauty or quality of something.

DIATOMS: a taxonomic group of phytoplanktonic protists (class Bacillariophyceae or Diatomophyceae) possessing a silica frustule or exoskeleton.

DICHLORVOS: is a synthetic, organic chemical used as an insecticide that does not occur naturally in the environment, but is manufactured by industry.

DIFUSE ATTENUATION COEFFICIENT: is the negative of the derivative with respect to the depth of the natural logarithm of a radiometric variable (e.g. radiance, downwelling or upwelling irradiance).

DINOFLAGELLATES: a taxonomic group of microplanktonic protists (phylum Dinoflagellata) which can be photosynthetic or phagotrophic (prey ingesting) characterized by two dissimilar flagella (transverse and longitudinal); some species are toxic.

DRIVERS: socio-economic sectors that fulfil human needs.

EARTH OBSERVATION: is the acquisition of information about the physical, chemical, and biological systems of the planet through remote sensing technologies to monitor and assess the status of and changes in the different environments.

ECHO-SOUNDER: equipment to measure depths. Works by sending acoustic pulses and return echo using the sound velocity in the water to determine distances to the bottom (e.g. depth).

ECOSYSTEM SERVICES: are benefits that humans freely gain from the natural environment and from properly-functioning ecosystems.

ECOTOXICOLOGICAL ASSESSMENT CRITERIA: assessment of the pollution status of the marine environment with respect to the damage to living cells and organisms.

ENDOCRINE DISRUPTOR: an exogenous substance capable of disrupting the normal function of the endocrine system.

ENVISAT: is ESA's successor to ERS. Envisat was one of the largest civilian Earth observation missions with 10 instruments aboard; it was launched in 2002 and ended on 8 April 2012. The more advanced imaging radar, radar altimeter and temperature-measuring radiometer instruments extended the ERS data sets. Additional data was supplemented by new instruments including a medium-resolution spectrometer sensitive to both land features and ocean colour.

EPIFLUORESCENCE MICROSCOPY: microscopy using a high powered light source (mercury bulb) that illuminates object from above, passing through different light filters that induce differential excitation and light emission by the object.

EQUIVALENT INHABITANTS: in wastewater treatment is the number expressing the ratio of the sum of the pollution load produced during 24 hours by industrial facilities and services to the individual pollution load in household sewage produced by one person in the same time.

ERS - EUROPEAN REMOTE SENSING (ERS) SATELLITES: ERS-1 and –2 that were launched into the same orbit in 1991 and 1995 respectively. Their payloads included a synthetic aperture imaging radar, radar altimeter and instruments to measure ocean surface temperature and wind fields.

ESTROGENIC EFFECTS: increase of female sex hormones in males.

EUKARYOTIC: cellular organization exhibiting membrane bound organelles such as nuclei, mitochondria and chloroplasts.

EUTROPHIC: ecosystem with high concentrations of nutrients; opposite is oligotrophic.

EUTROPHICATION: the enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorus, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned.

EXOENZYMATIC HYDROLYSIS: breakdown of hydrogen bonds in organic molecules by bacterial extracellular enzymes.

FETCH: is the uninterrupted distance over the sea for which the wind blows without a change in direction and that affect the growth of wind waves.

FLAGELLA: external organelles of some protists used for locomotion and prey capture

FLAT PLAINS: in this book, flat plains refer to horizontal areas that lack substantial ripples or hills, and are situated under the effects of tides (intertidal flat areas).

FORESHORE: is the zone between mean low water and the seaward berm, which is equivalent to the upper limit of wave uprush at high tide.

FRUSTULES: silica exoskeletons of diatoms.

GEOMORPHOLOGY (GEOMORPHIC): is the scientific study of the origin and evolution of topographic and bathymetric features created by physical, chemical or biological processes operating at or near the Earth's surface.

GEOSTACIONARY PLATFORM: is an earth-orbiting satellite, placed at an altitude of approximately 35,800 km directly over the equator, that revolves in the same direction as the rotation of the earth (west to east). At this altitude, one orbit takes 24 hours, the same length of time as the earth requires to rotate once on its axis. The term geostationary refers to the nearly stationary position of the satellite in the sky, as seen by a ground-based observer.

GLUTERALDEHYDE: organic fixative widely used to prepare samples for microscopy.

GONOCHORISTIC GASTROPODS: the state of having just one of at least two distinct sexes in any one individual gastropods.

GRAVIMETRIC THICKENING: is the first step, often unavoidable, of reducing the volume of sludge by removing water in settling-thickening tanks the suspended solid particles that are heavier than water settle out in the bottom of the tank through gravitational sedimentation.

GROUNDWATER: water that occurs below the surface of Earth, where it occupies all or part of the void spaces in soils or geologic strata.

HALOGENS: a group in the periodic table consisting of five elements with similar chemical structures and properties: fluorine (F), chlorine (Cl), bromine (Br), iodine (I), and astatine (At).

HEPTACHLOR: organochlorine compound that was used as an insecticide.

HETEROTROPHIC BACTERIA: bacteria that absorb dissolved organic matter from medium.

HYDRODINAMIC: science that deals with the water motion and forces acting on objects moving in water.

HYDROPHOBIC: substances that cannot be mixed with or dissolved in water.

HYDROSEDIMENTARY PROCESSES: processes involving the transport of sediment by currents and waves.

HYPOXIA: low concentrations of dissolved oxygen in water or the physiological state resulting from low oxygen in tissues.

IMPOSEX: imposition of male characteristics on females in prosobranch molluscs.

INTERTIDAL AREA: the intertidal area, also known as intertidal zone, foreshore and seashore and sometimes referred to as the littoral zone, is the area that is above water at low tide and underwater at high tide, meaning the area between tide marks.

INTERTIDAL MUD FLATS: shallow-sloped shoreline, with expanses of fine sediment. They are found in sheltered areas such as bays, bayous, lagoons, and estuaries.

JETTIES: shore-connected structures generally built on either one or both sides of the navigation channel, perpendicular to the shore and extending into the ocean.

KU-BAND: refers to the portion of the electromagnetic spectrum in the microwave range of frequencies from 12 to 18 gigahertz (GHz).

LANDSAT: represents the world's longest continuously acquired collection of space-based moderate-resolution land remote sensing data. The acquisition of this data is a joint initiative between the U.S. Geological Survey (USGS) and National Aeronautics and Space Administration (NASA over four decades.

LIGAND: is an ion or a molecule that binds to a central metal atom to form a complex.

LIPOPHILIC: ability of a chemical compound to dissolve in fats, oils, lipids, and non-polar solvents such as hexane or toluene.

LONGSHORE DRIFT: is the movement/transport of (beach) sediments approximately parallel to the coastline.

MANGROVE: tidally influenced wetland ecosystem within the intertidal zone of tropical and subtropical latitudes. Mangrove also designates the marine tidal forest that includes trees, shrubs, palms, epiphytes and ferns.

MARINE STRATEGY FRAMEWORK DIRECTIVE: aims to achieve Good Environmental Status (GES) of the EU's marine waters by 2020 and to protect the resource base upon which marine-related economic and social activities depend.

MESOTROPHIC: an intermediate range in nutritional regime between eutrophic and oligotrophic.

METABOLISM: sum of all chemical reactions that occur within a living cell.

MICROGRAZERS: microscopic protists that ingest prey.

MICROORGANISMS: a microorganism is a microscopic organism, which may exist in its single-celled form or in a colony of cells.

MORPHOSEDIMENTARY FEATURES: geological forms composed by sediment.

MPN: is a statistics-based test which estimates the number of fecal coliforms in a water sample based on the degree of lactose fermentation by organisms in the sample.

MUDFLATS: are coastal wetlands that form when mud is deposited by tides or rivers. They are found in sheltered areas such as bays, bayous, lagoons, and estuaries.

MULTI-SPECTRAL IMAGERY: is produced by sensors that measure reflected energy within several specific bands of the electromagnetic spectrum. Multispectral sensors usually have between 3 and 10 different band measurements in each pixel of the images they produce.

NATURA 2000: is a network of protected sites which are core breeding and resting sites for rare and threatened species, as well as rare natural habitat types. It stretches across all 28 EU countries, both on land and at sea. The aim of the network is to ensure the long-term survival of Europe's most valuable and threatened species and habitats, listed under both the Birds Directive and the Habitats Directive.

NEOGASTROPOD: taxonomic order within the class Gastropoda.

OCEAN COLOUR SENSOR: is any instrument for remote sensing of ocean colour, usually from aircraft or satellites.

OCEAN COLOUR: is a generic term referring to the spectral dependence of the radiance leaving a water body.

OLIGOTROPHICATION: tendency towards an oligotrophic or low nutrient regime.

ORGANOMETALLIC COMPOUNDS: chemical compounds containing at least one chemical bond between a carbon atom of an organic molecule and a metal.

ORGANOTIN COMPOUNDS: chemical compounds based on tin with hydrocarbon substituents.

OVERWASH: is the flow of water and sediment over a coastal dune or beach crest during storm events (or other situations carrying high water levels).

OXIDATIVE DAMAGE: disturbance in the balance between the production of reactive oxygen species (free radicals) and antioxidant defenses.

PHAEOPIGMENTS: degraded photopigments.

PHAGOTROPHIC PROTISTS: eukariotic microorganisms that ingest prey.

PHOTOINHIBITION: is a light-induced reduction in the photosynthetic capacity of a plant, alga, or cyanobacterium. The term photoinhibition can also be used to describe all reactions that decrease the efficiency of photosynthesis when plants are exposed to light.

PHOTOSYNTHETIC ORGANISMS: also known as photoautotrophs, are organisms that are capable of capturing the energy from sunlight and using it to produce organic compounds. This process, known as photosynthesis, is essential to life as it provides energy for both producers and consumers. These organisms include higher plants, algae and bacteria.

PHYLOGENETIC RESEARCH: in biology, phylogenetics is the study of the evolutionary history and relationships among individuals or groups of organisms (e.g. species or populations). These relationships are discovered through phylogenetic inference methods that evaluate observed heritable traits, such as DNA sequences or protein structures.

PHYTOESTABILIZER: plant with capacity to carry out phytostabilization. In this process, chemical compounds produced by the plant immobilize some contaminants.

PHYTOPLANKTON: are small (linear sizes from less than 1 to tens of μm), usually single-cell (some form chains several hundred μm long), aerobic (living in oxygenated environments), photosynthetic (pigmented, containing chlorophyll a and using sunlight), oxygenic (producing oxygen) organisms; may be prokaryotes (e.g., cyanobacteria) or eukaryotes (e.g., protists and chlorophytes); most are not plants.

PICOFLAGELLATES: very small flagellated protists (0.2 - 2 μm cell sizes).

PLANT EXUDATE: is any substance that oozes out from the pores of plant tissue. Resins gums, oils and lacquers are examples of exudates widely extracted for industrial uses.

PLUMES: in hydrodynamics, a plume is a column of one fluid moving through another.

PRIMARY PRODUCERS: organisms that acquire their energy from sunlight and mineral sources.

PROKARYOTIC: cellular organization of bacteria without membrane bound organelles such as nuclei.

PURE STAND: a plant population consisting exclusively of members of one species.

PYROLYTIC ORIGIN: thermal decomposition of materials at elevated temperatures.

RADIOISOTOPES: radioactive substrates used to determine for instance primary abd bacteria production.

RAMSAR CONVENTION: is the intergovernmental treaty that provides a framework for the conservation and wise use of wetlands and their resources.

REDOX REACTIONS: chemical reactions involving lost (oxidation) and gain (reduction) of electrons.

REFLECTANCE: is the ratio of the total amount of radiation, as of light, reflected by a surface to the total amount of radiation incident on the surface.

REFLECTIVE BEACHES: are beaches characterised by a relatively steep narrow beach face, composed of coarse sand, a narrow surf zone and often have cusps on the upper part of the beach; they present the lowest wave energy of the wave-dominated beaches.

REMINERALISATION: transformation of organic matter into its simplest inorganic forms.

RESIDENCE TIME: the average time for which a particular molecule of water will remain in a body of water.

RHIZOME: is a modified subterranean plant stem that sends out roots and shoots from its nodes.

RHIZOSEDIMENTS: sediments colonized by plants.

RTK-DGPS - REAL TIME KINEMATIC DIFFERENTIAL GLOBAL POSITION SYSTEM: equipment to measure position with cm accuracy that makes uses of the several satellites in orbit.

SALT MARSH (OR SALTMARSH): is the low, wet, muddy area periodically or continuously flooded by brackish or salt water. They are usually characterized by grasses and other low plants.

SEAGRASS: is a group of flowering plants found in marine or estuarine waters, that tend to develop extensive underwater meadows.

SECONDARY PRODUCTION: the generation of biomass of heterotrophic (consumer) organisms in a system.

SEDIMENTS: is a naturally occurring materials that are broken down by processes of weathering and erosion, and are subsequently transported by the action of wind, water, ice, or by the force of gravity acting on the particles.

SEMIDIURNAL TIDES: tidal changes of level twice in a lunar day.

SHOREFACE: is the active littoral zone off the low water line. This zone extends seaward from the foreshore to some distance beyond the breaker zone. The littoral zone is the zone in which the littoral processes take place; these are mainly the longshore transport, also referred to as the littoral drift, and the cross-shore transport.

SHORELINE: is the interface between land and sea.

SLOPPY FEEDING: dissolved organic matter loss during prey ingestion or phagotrophy.

SPECIATION OF METALS: are the different chemical forms/species that a metal can exist.

SPECTRAL BACKSCATTERING: consists of the scattering of radiation or particles in a direction opposite to that of the incident radiation due to reflection from particles of the medium traversed.

SPECTRAL BANDS: are a limited range of values that a sensor is set to detect along a spectrum.

SPIT: narrow and elongated coastal landform attached to the mainland generated.

SPOT - "SATELLITE POUR L'OBSERVATION DE LA TERRE": is a commercial high-resolution optical imaging Earth observation satellite system operating from space.

SWASH ZONE: is the zone of wave action on the beach, which moves as water levels vary, extending from the limit of run-down to the limit of run-up.

SWATH: is the surface area of the earth observed by a spaceborne sensor, generally, varying between tens and hundreds of kilometers wide.

SWELL: are waves with high wavelength, generated at the sea and that travelled far from their place of origin.

SYNOPTIC SCALE: covers views of large areas of, for example, the earth surface.

SYNTHETIC APERTURE RADAR: produces a microwave signal from a sensor platform borne above the earth's surface, for example, on aeroplanes or satellites. The signal is directed to the surface and the subsequent backscattered waves are reflected directly back to a receiver on the same platform.

T90 - THE BACTERIAL DECAY RATE IS OFTEN EXPRESSED AS T90: time for bacterial concentration to decrease by 90%. Bacterial inactivation in natural waters is driven by a number of interacting processes. The main driver is the intensity of the incident irradiance from sunlight. In coastal waters the decay rate of faecal bacteria is also affected by and temperature.

TIDAL CREEKS: is the portion of a stream that is affected by ebb and flow of ocean tides.

TIDAL FLATS: Tidal flats are intertidal, soft sediment habitats (formed by mud, sand or a mixture of both), found between mean high-water and mean low-water spring tide, and are generally located in estuaries, lagoons or other low energy marine environments.

TIDAL INLETS: is a narrow channel that connects the open sea with a lagoon.

TOXICITY: degree to which a chemical substance or a particular mixture of substances can damage an organism.

TRACE METALS: are a group of metals that includes both heavy and transitional elements present in small amounts in vegetal and animal cells. There are two types, the micronutrients that are essential for health and those that have no known biological function. All trace metals have the potential to be toxic when present in excessive concentrations.

TSS - TOTAL SUSPENDED SOLIDS: is the dry-weight of suspended particles, that are not dissolved, in a sample of water that can be trapped by a filter that is analyzed using a filtration apparatus.

UV DESINFECTION: is a disinfection method that uses short-wavelength ultraviolet (UV-C) light to kill or inactivate microorganisms by destroying nucleic acids and disrupting their DNA, leaving them unable to perform vital cellular functions.

VIRAL LYSES: cellular break-up induced by viral infections.

WASTE WATER: is any water that has been affected by human use. Wastewater is "used water from any combination of domestic, industrial, commercial or agricultural activities, surface runoff or stormwater, and any sewer inflow or sewer infiltration".

WATER FRAMEWORK DIRECTIVE: protects and enhances freshwater resources with the aim of achieving a good status for EU waters; its scope extends beyond lakes, rivers, and groundwaters to transitional and coastal waters.

WAVE PROPAGATION: is any of the ways in which waves travel.

WAVE-SETUP: is the increase in mean water level due to the presence of breaking waves.

WETLANDS: areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters. Wetlands may incorporate riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than six meters at low tide lying within the wetlands.

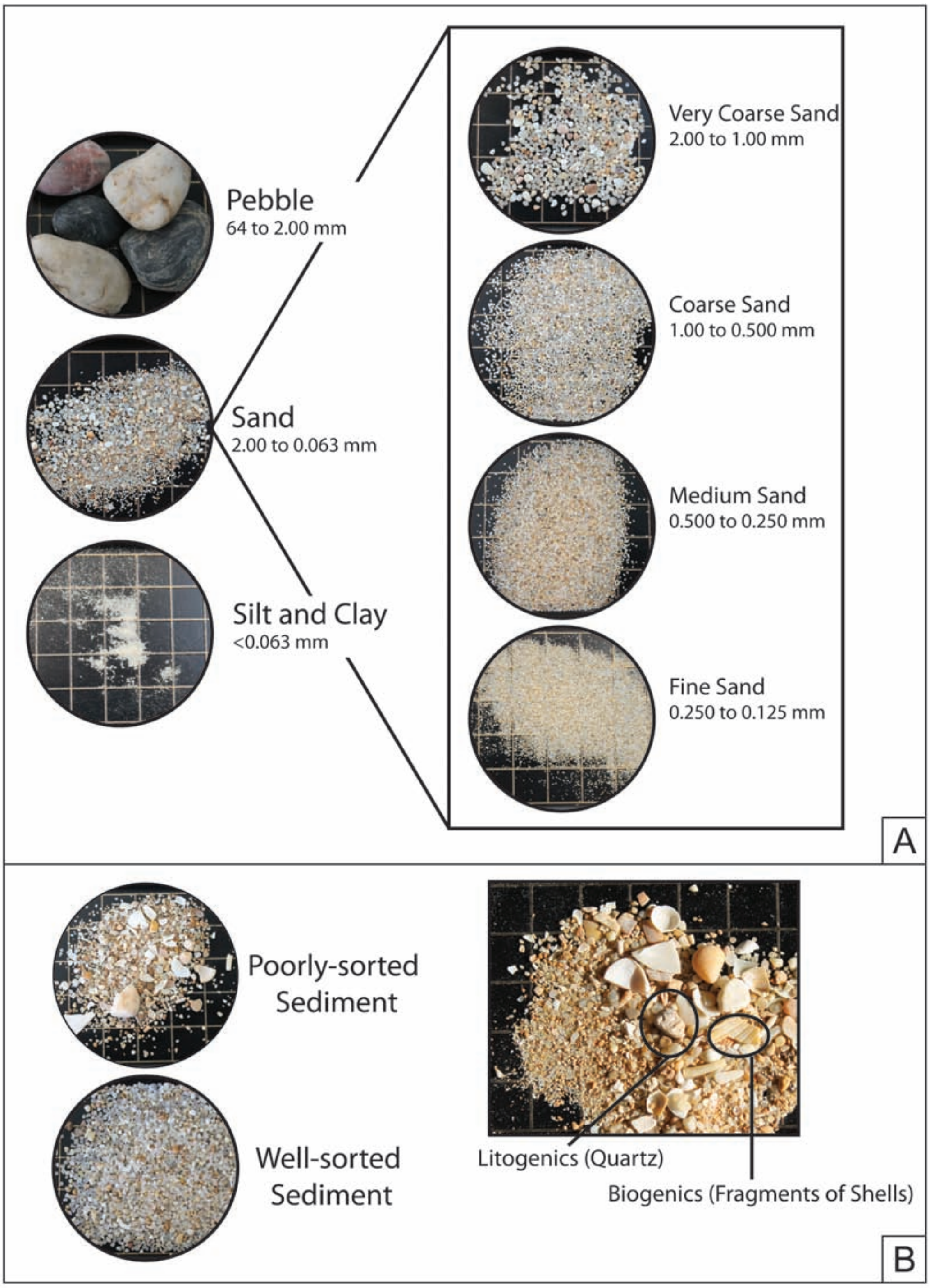
Annexes

Million years	Eon	Era	Period	Epoch	
	PHANEROZOIC	CENOZOIC	QUATERNARY	HOLOCENE	From the Greek *holos* (whole) and *kainos* (new). End of the Pleistocene glaciations. Rise of Human civilization (Stone, Bronze and Iron Ages).
0,011				PLEISTOCENE	From the Greek *pleistos* (most) and *kainos* (new). Climatic instability with successive cycles of glacial-interglacial. Evolution of anatomically modern humans.
2,6			NEOGENE		Means "new- born". Diversity of horses and mastodons. Appearance of *Homo habilis*.
24			PALEOGENE		Means "ancient- born". Formation of the Antarctica ice cap Appearance of several modern mammals.
65		MESOZOIC	CRETACEOUS		From chalk the rock forming the cliffs of the English Channel. Flowering plants proliferate and many types of insects.
114			JURASSIC		Jura mountains between France and Switzerland. Many types of dinosaurs. Mammals were small yet common. First birds.
213			TRIASSIC		From trias, the three phases of folding affecting the European rocks. Dinosaurs dominant on land and appearance of the first mammals and crocodilian.
248		PALEOZOIC	PERMIAN		Perm province from the ex USSR. Amphibians remain common.
286			CARBONIFEROUS		Coal deposits. First reptiles.
360			DEVONIAN		Devonshire, England. First trees and insects.
408			SILURIAN		Siluros Celtic tribe of Wales. Early corals. First vascular plants and fishes.
438			ORDOVICIAN		Ordovico Celtic tribe of Wales. Diversity of invertebrates. Early corals.
505			CAMBRIAN		Cambria was the Roman name of Wales. Major diversification of life.
541	PROTEROZOIC				
4 600					

Annex I

Geological Time Table

This organization of the geological time since the Earth origin (4 600 million years ago) is a very simplified version. Note that the graduated scale of ages is not proportional to the lasted interval of Periods and Eras. It was a functional option to fit one page and still contain additional information. Credits: D. Moura & A. Gomes.

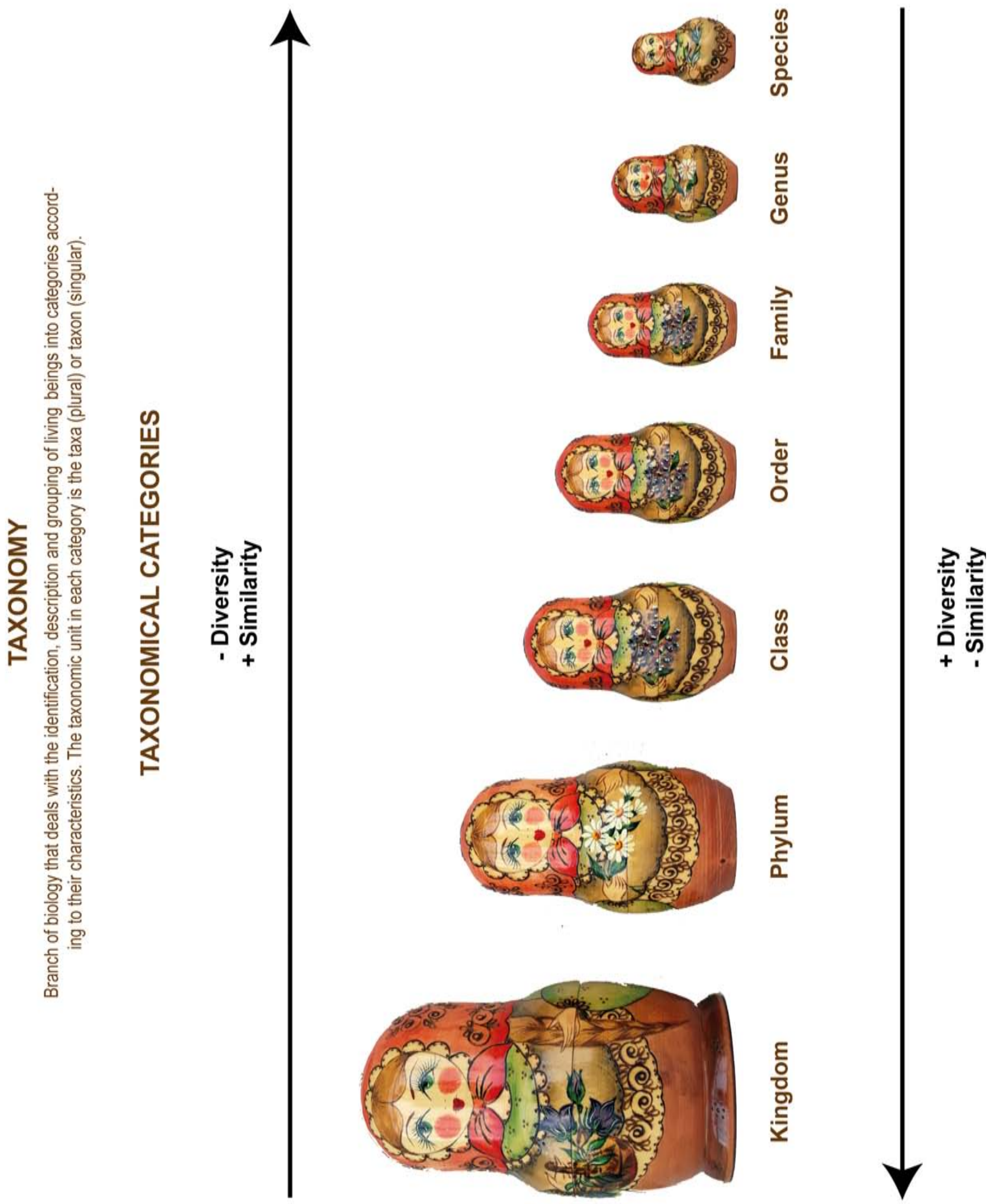


Annex II

Sediment grain size and sorting

These images represent the grain size dimensions in millimetres (mm) from pebbles to silt and clay (A) and the degree of uniformity of grain size: sorting (B).

Credits: Sónia Oliveira (CIMA)



Annex III

Taxonomy and Taxonomical Categories

Credits: Ana Gomes (ICArEHB) & Jaime Aníbal (CIMA)

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