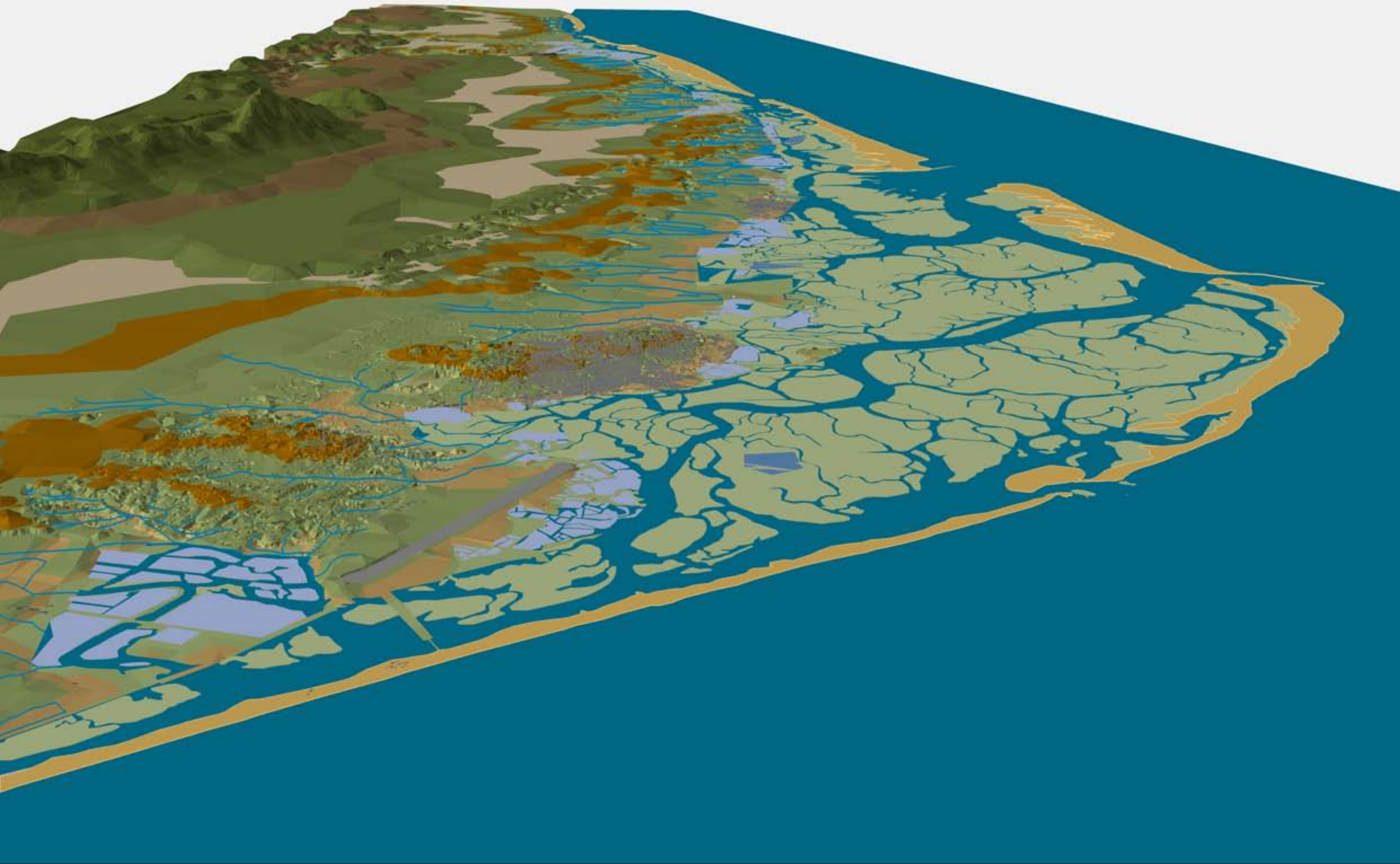

RIA FORMOSA

Challenges of a coastal lagoon in a changing environment

Edited by

Jaime Aníbal, Ana Gomes, Isabel Mendes & Delminda Moura

UAlg CIMA

UNIVERSIDADE DO ALGARVE

CENTRO DE INVESTIGAÇÃO MARINHA E AMBIENTAL

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

Sónia Cristina[1], John D. Icely[1,2] & Alice Newton[1]

[1] Centre for Marine and Environmental Research (CIMA), University of Algarve, Cmpus de Gambelas, 8005-139 Faro

[2] Sagremarisco, apartado 21, Vila do Bispo, 8650-999 Vila do Bispo, Portugal

sccristina@ualg.pt; john.icely@gmail.com; anewton@ualg.pt

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.

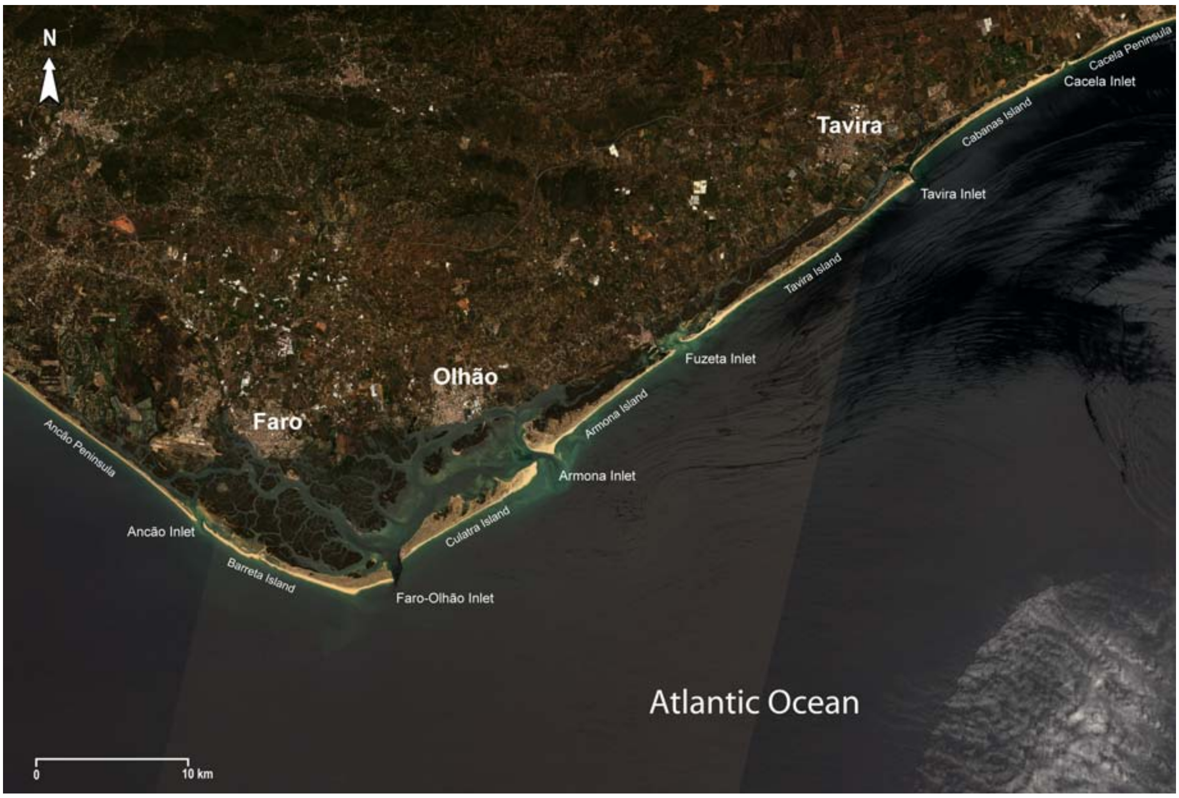

Figure 10.1.
Satellite image on the 20 May 2016 from Sentinel-2 Level-1C showing the Ria Formosa lagoon.

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.

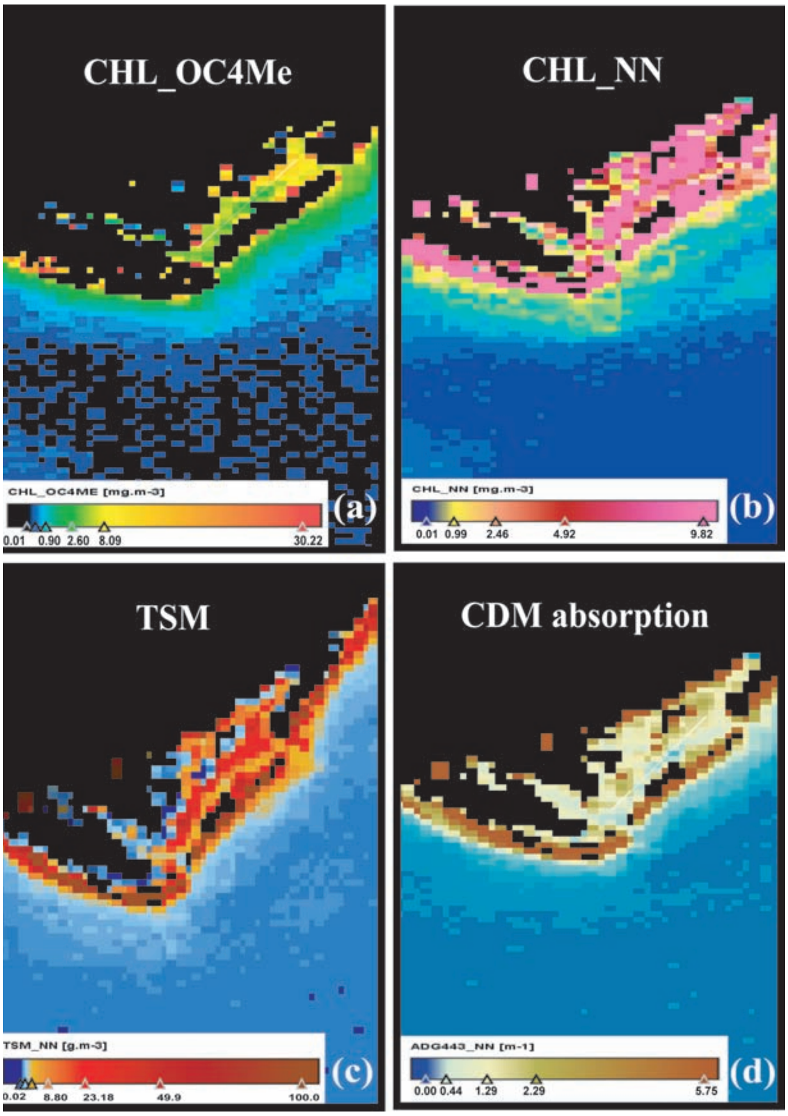

Figure 10.2.
Satellite image on the 16 November 2017 from the OLCI ocean colour sensor of Sentinel-3A showing the central section of the Ria Formosa. The different water products derived from the image include: **(a)** chlorophyll from the CHL_OC4Me algorithm, **(b)** chlorophyll from the CHL_NN algorithm, **(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.

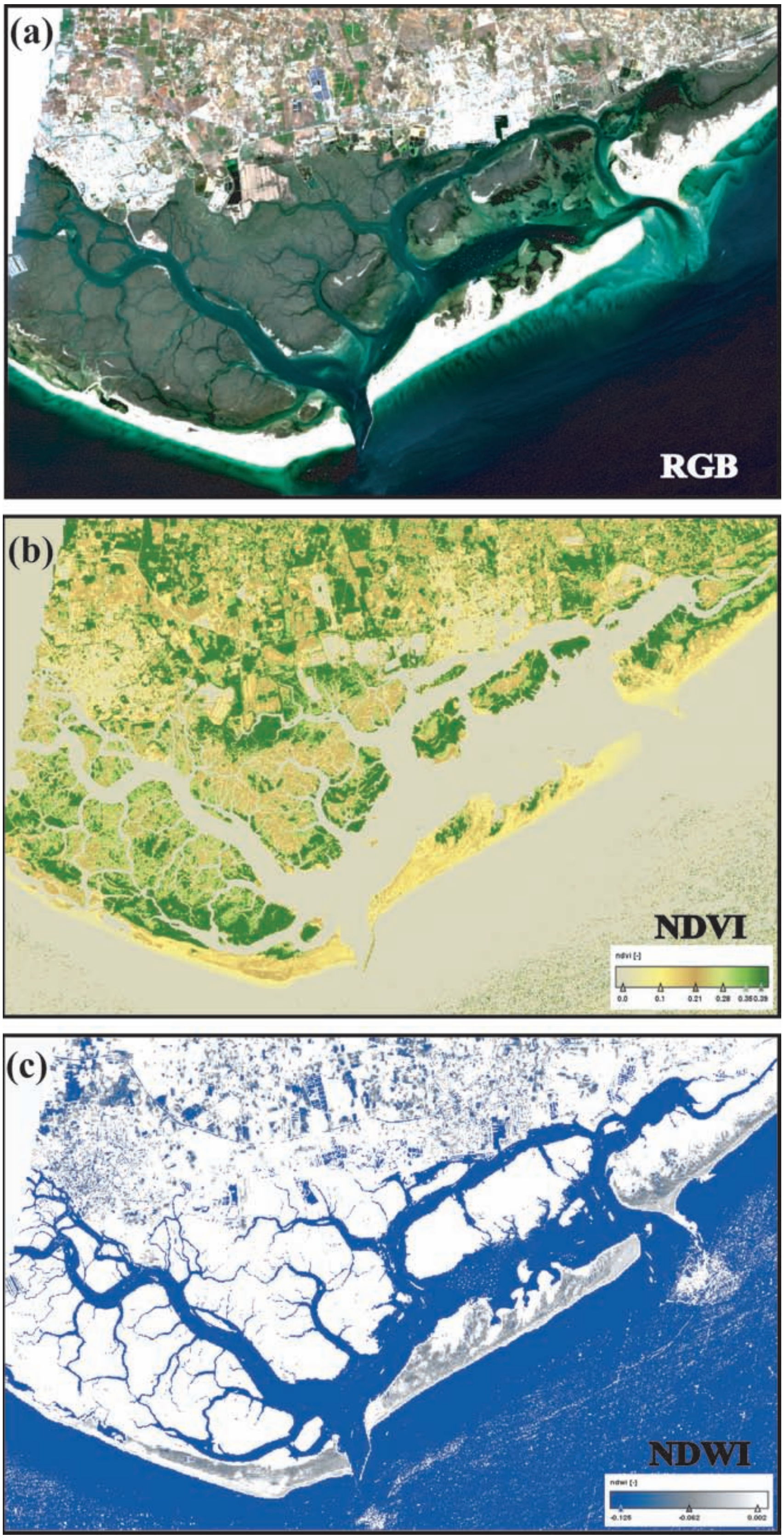

Figure 10.3.
Sentinel-2A MSI Level 2 image of the Ria Formosa on 6 of July 2018 where **(a)** is the RGB image which has been processed in **(b)** with the vegetation radiometric index (NDVI-Normalized Difference Vegetation Index), where the value between -1 (beige colour) correspond to water and the 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).

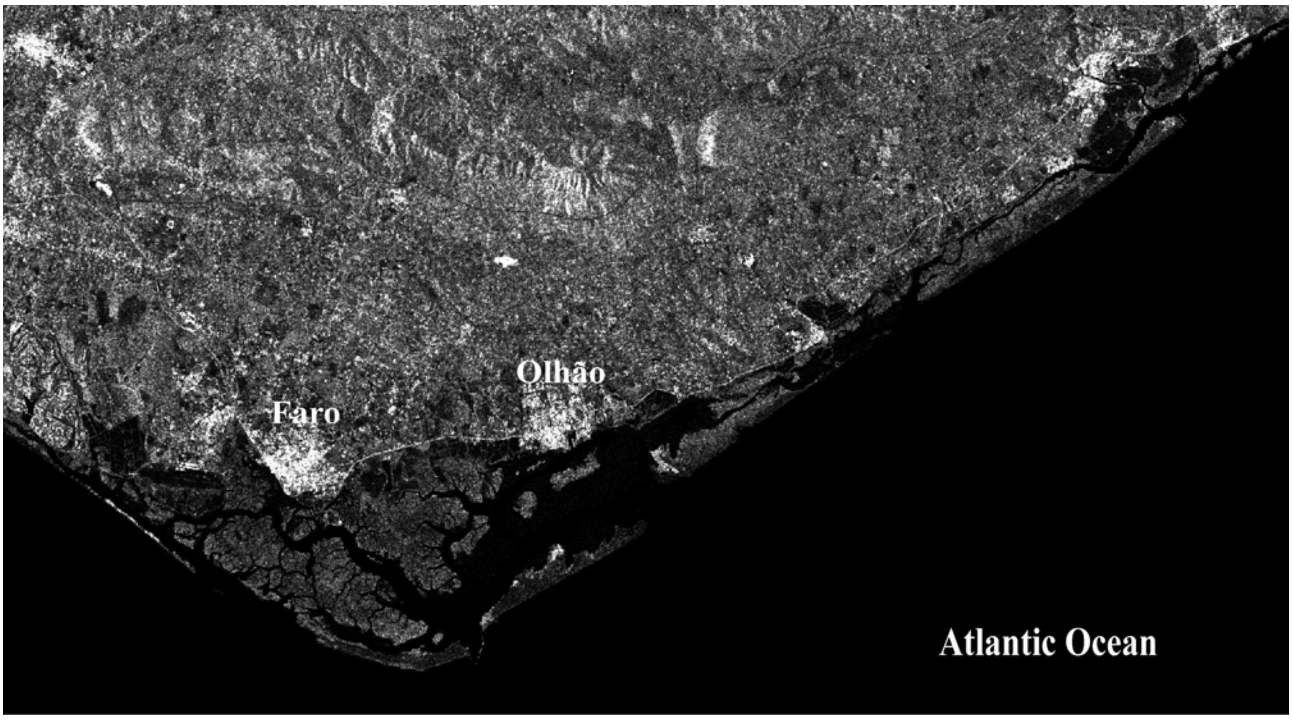

Figure 10.4.
Sentinel-1A satellite image of the Ria Formosa on 14 July 2018.

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.

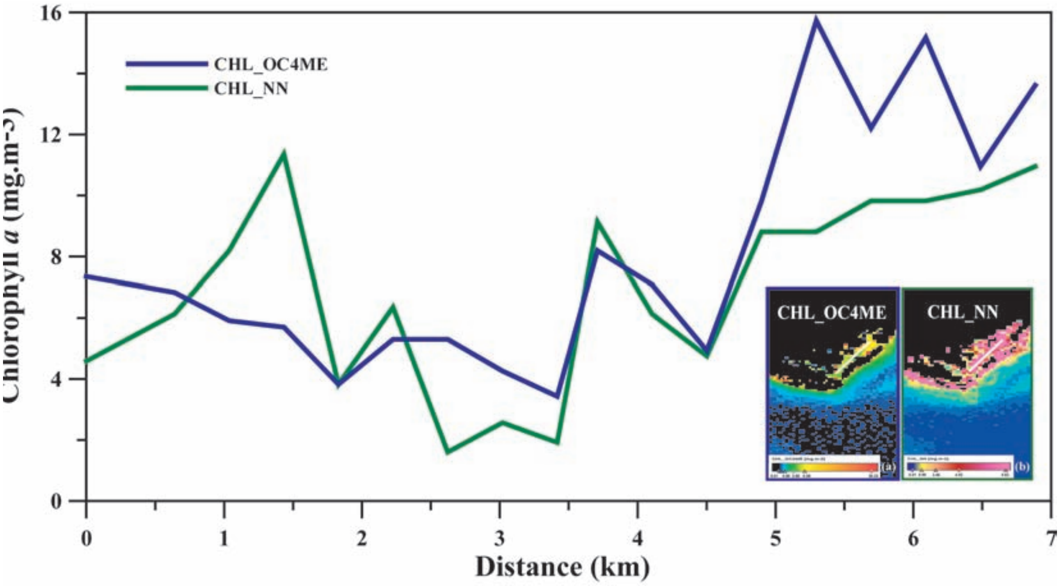

Figure 10.7.
Sentinel-3A OLCI transects, extending from Faro-Olhão to Armona Inlet of the Ria Formosa on 16 November 2017, comparing chlorophyll *a* concentrations retrieved by the algorithms CHL_OC4Me (blue line) and CHL_NN (green line). The transects have been extracted from the Sentinel-3A OLCI satellite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

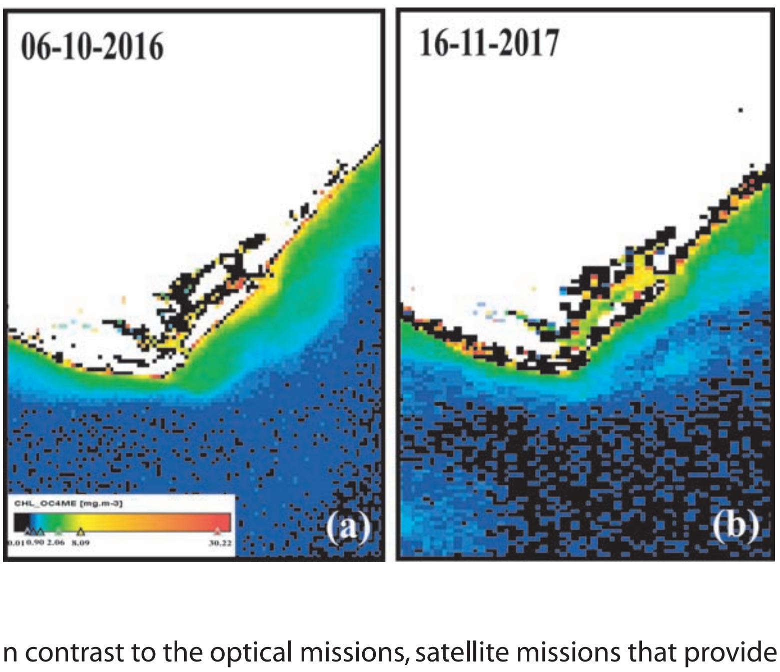

Figure 10.8.
Sentinel-3A OLCI CHL_OC4Me algorithm when the Ria Formosa is at low tide (a) and between low and high tide condition (b), where the white pixels represent the land, respectively on 6th October 2016 and on 16th November 2017.

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.

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