Lagoons for LIFE

The role of Earth Observation in supporting holistic coastal lagoon management

An initiative of futurearth coasts land-ocean interactions in the coastal zone

Recommended Citation: Lagoons for Life, 2025. White Paper - The role of Earth Observation in supporting holistic coastal lagoon management. Published online by the Lagoons for Life initiative of the Future Earth Coasts programme. 25 July 2025. DOI: 10.5281/zenodo.16419456

Acknowledgements: The Authors wish to thank the following for their valuable insights and comments when peer-reviewing the White Paper: Professor *Alice Newton* (Center for Marine and Environmental Research (CIMA), Universidade do Algarve; Aquatic Research Network (ARNET)), Dr *Adriana Maria Constantinescu* (Romanian National Institute for Marine Geology and Geoecology (GeoEcoMar)).

Gema Casal's contributions were supported by funding from Ramón y Cajal 2023 grant RYC2023-044898-I funded by the Spanish State Plan for Scientific and Technical Research and Innovation 2021–2023. Sónia Cristina's contributions were supported under the programme contract CEECINSTLA/00018/2022 funded by the Portuguese Foundation for Science and Technology (FCT) for the performance of research activities at CIMA (https://doi.org/10.54499/UIDB/00350/2020) under the scope of the Associated Laboratory ARNET (LA/P/ 0069/2020) (https://doi.org/10.54499/LA/P/0069/2020).

Cover image: Fishing boats in Chilika Lake, India (bought on Shutterstock).

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This report has been prepared by the Lagoons for Life network following a peer review process and represents the views of the authors. The report does not necessarily reflect the opinions or policies of affiliated organisations.

Contents

About Lagoons for Life

Lagoons for Life is a global initiative under the Future Earth Coasts programme that brings together natural and social scientists to co-develop holistic sustainable management strategies for coastal lagoons around the world. The initiative focuses on the potential and challenges for satellite Earth Observation (EO) and looks at how EO, in combination with other data sources, can support and add value to coastal lagoon management.

Having recognised a data and knowledge gap in the systematic study of coastal lagoons, Lagoons for Life adopts a holistic approach, by integrating environmental, social and economic datasets from multiple sources. Through linking with international experts, stakeholders, researchers and scientists, we aim to co-design informed coastal lagoon management strategies that address current and future issues in coastal lagoon social-ecological systems.

Executive Summary

Coastal lagoons, representing 13% of the world's coastline, are dynamic and globally significant ecosystems that serve as vital habitats for diverse species, provide crucial ecosystem services, and support the livelihoods of millions of people. These unique systems are characterised by their position at the interface of land and sea, acting as complex socio-ecological systems where environmental and human dynamics are deeply interconnected. Despite their importance, coastal lagoons are understudied and often overlooked in national and international policies due to their transitional nature, neither fully marine nor fully terrestrial.

This White Paper emphasises the urgent need to address the data, knowledge, and management gaps surrounding coastal lagoons. It highlights the applicability of EO as a transformative tool for advancing holistic and sustainable lagoon management. EO can provide critical insights into the physical, ecological, and social dimensions of coastal lagoons, addressing limitations in current approaches and complementing other data sources. The paper also identifies the challenges associated with EO technologies, including the need for algorithm validation, data standardisation, and enabling data accessibility to under-resourced regions, and provides a set of bullet points with further recommendations. Overall, the White Paper argues that coastal lagoons, with their distinctive characteristics and critical role in ecosystems and communities, demand global attention.

Abstract

Coastal lagoons are complex and dynamic transitional ecosystems that form an interface between freshwater and marine waters, resource rich and heavily influenced by human activities. Management of lagoon systems is not only complex because of the wide range of co-located activities and interests (e.g., economic vs. conservation), but also because the natural status of lagoons is affected by anthropogenic pressures (e.g., pollution) and climate change impacts (e.g., sea level). In addition, they are systems with great spatial and temporal variability under naturally fluctuating conditions, making them inherently ever-changing systems, and meaning that they exist within a naturally evolving life cycle of bio-physical change. Providing a framework that informs coastal lagoon management should address the challenges of (i) **monitoring and understanding processes** of global environmental change; (ii) **predicting risks, understanding and mitigating consequences** for current and future extractive and non-extractive resource utilisation; and (iii) **forecasting** the bio-physical evolution of coastal lagoon systems under both natural and anthropogenically altered conditions. Such a framework requires data that are spatially and temporally explicit, and measure, either directly or via a proxy, a set of indices and indicators that reflect the link and association between the biophysical components of lagoon systems with the resources and ecosystem services that underpin anthropogenic exploitation. Research and technological development play a key role in this. This White Paper, based on expert knowledge, aims to give a broad vision on the state of knowledge of coastal lagoons and present the potential and limitations of Earth Observation (EO) technologies to support a holistic management approach. Finally, it provides actionable recommendations to address the challenges of applying EO in coastal lagoon systems, including enhancing interdisciplinary collaboration, improving algorithm development and validation, promoting global initiatives, and fostering capacity-building in resource-limited regions.

Introduction

Coastal lagoons are globally important, yet understudied, coastal systems. They account for 13% of the world's coastline (Barnes, 1980; Kjerfve, 1994) and represent a unique mosaic of social, cultural, political-economic, and ecological characteristics (Figure 1). Directly and indirectly, lagoons play a critical role in providing livelihood opportunities for humans and offer essential habitat for several marine and brackish water species. They are host to a significant portion of the planet's biodiversity contributing to support the 40% of the world's population living within 100 km from the coast (Neumann et al., 2015; UN, 2010), with an estimated 1.09 billion people living just within 10 km from the coastline in 2018 (Cosby et al., 2024). While resources in coastal areas are fast becoming major attractions from the point of both conservation and human wellbeing, accelerating growth rates of the global coastal population observed in recent years and projected for the coming years (Cosby et al., 2024; Reimann et al., 2023) add pressure to coastal systems and increase coastal risks (Reimann et al., 2023). In addition, several lagoon systems of the world are experiencing a peculiar "identity" crisis, partly because of the ongoing processes of change (Coulthard, 2008; Nayak, 2014) in their socio-ecological attributes, but particularly because of a lack of recognition of their unique position at the nexus of land, freshwater, sea and atmosphere. Coastal water bodies such as estuaries and lagoons, despite being among the most productive aquatic systems (Alongi, 1998; Pérez-Ruzafa et al., 2024), often represent "grey zones" for fisheries monitoring, research and policy making (Pérez-Ruzafa and Marcos, 2012). Lagoons are neither "marine" nor "inland", but a transitional ecosystem between both domains (Pérez-Ruzafa et al., 2011; Tagliapetra et al., 2009) and, as such, risk being overlooked by fisheries and other national and international policies. In Europe, coastal lagoons are declared as habitats of high natural value (type 1150*) in the Habitats Directive (92/43/EEC). However, they are completely absent in the European Union's (EU) Marine Strategy Framework Directive (MSFD) 2008/56/EC. With the lagoon socio-ecological context remaining by large a neglected area, existing work on coastal lagoon systems has remained comparatively limited and, even though there is a growing body of literature concerning lagoon systems (Box 2), the comparison with existing literature on marine and terrestrial systems demonstrates significant gaps.

This White Paper gathers multidisciplinary expert insights to highlight the unique role of coastal lagoons as systems where social and ecological connections converge. It also emphasises the potential of remote sensing (Earth Observation, EO) in supporting integrated and holistic coastal lagoon management. The paper examines available knowledge on coastal lagoon issues, identifies gaps in knowledge, understanding, and methodologies, and explores how new technologies, such as EO, can address these challenges. The potential of EO for coastal lagoon management is discussed, showcasing its ability to fill critical knowledge and data gaps and contribute to innovative management strategies. While recognising its benefits, the paper also addresses the limitations of EO, including technological and methodological challenges, and offers an outlook on future advancements in remote sensing. Building on evidence of the high sensitivity of coastal lagoons to environmental and human-induced changes, it underscores what remains missing in current approaches.

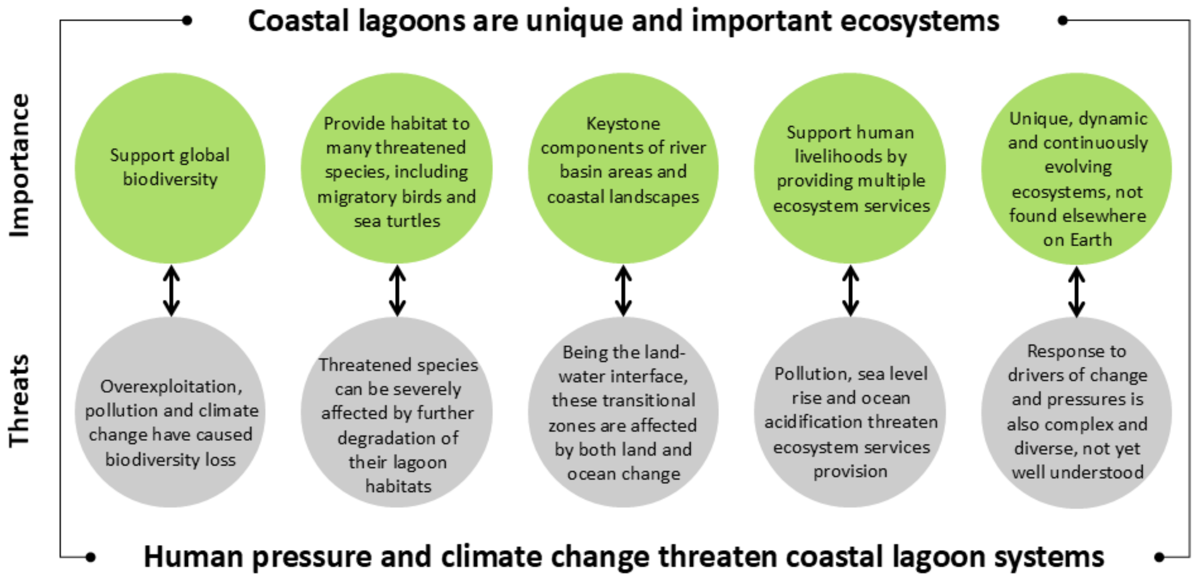

Figure 1. *Coastal lagoons represent a unique mosaic of social, cultural, political-economic and ecological characteristics.*

Coastal Lagoon: A Terminology Challenge

The term "coastal lagoon" encompasses a high variable number of coastal environments and has been described differently across disciplines and regions. Some definitions emphasise their semi-enclosed nature and limited oceanic exchange, while others focus on salinity gradients or morphological criteria. In addition, coastal lagoons share many features and processes with other aquatic ecosystems in the transition between land and sea. This diversity in defining characteristics creates difficulty in distinguishing lagoons from other coastal systems like estuaries, bays, or tidal flats. Different regions adopt local terms for similar systems, further complicating the global understanding of what constitutes a coastal lagoon. Comparing studies from different regions or disciplines becomes challenging when terminological inconsistencies arise. Worldwide, there are differences in the terminology to refer to these environments: *coastal lagoons, coastal lakes, semi-enclosed bays, estuaries and rías, lagons, lagunas, lagoas, lagunes, étangs, ponds, albuferas, brednings, caletas, cienagas, marismas, esteros, marsh, marais, marios, stagni, sacca, limans, limnothalassas, zalews, SECS* (semi-enclosed coastal systems), or the more recent terms *ICOLLs* (intermittently closed and open lakes and lagoons) and *RRE* (regions of restricted exchange) (Pérez-Ruzafa et al., 2019). For example, in certain cases coastal lagoons adopt the same title as freshwater habitats (e.g., Lake Menzalah, Egypt, or Swan Pool, United Kingdom) or other type of coastal systems (e.g., Great South Bay, USA). It also happens that names of other water bodies which include the term lagoon do not correspond to these systems (e.g., Knysna Lagoon, South Africa, which is an estuary). In attempts to include all this variability (Box 1), several definitions for "coastal lagoons" have been proposed in the past (e.g., Kjerfve, 1994; Tagliapietra et al., 2009).

Box 1. What are coastal lagoons?

Several definitions of coastal lagoons have been proposed (see Tagliapietra et al., 2009 for a full review). Traditionally, coastal lagoon systems are defined as *surface water bodies that are separated from the ocean by a barrier, connected to the ocean by one or more restricted inlets which remain open at least intermittently*, and have water depths which seldom exceed a few meters. Coastal lagoons are found on all continents, except Antarctica, and in various forms. *A lagoon may or may not be subject to tidal mixing, and salinity can vary from that of a coastal freshwater lake to a hypersaline saline pan, depending on the hydrological balance.*

Most coastal lagoons formed during the Holocene as a result of rising relative sea level and the construction of coastal barriers by marine processes. Since barrier islands form during rises in relative sea level, lagoons are a common feature along coasts experiencing such conditions (Duck & Silva, 2012). On the contrary, in regions where isostatic uplift exceeds eustatic sea level rise, lagoons are relatively rare (Martin & Dominguez, 1994). Coastal lagoons are also formed over time when material brought downstream in an estuary builds up, eventually cutting off the estuary from the ocean. These coastal lagoons are usually freshwater input dominated.

Figure Box-1. *Karavasta Lagoon, Albania. Image source: ESA Copernicus Sentinel 2B satellite, 15.03.2017*

Coastal lagoons also present high variability in their geomorphological, hydrological and ecological conditions that give rise to various classification systems. They are dynamic aquatic ecosystems with a high natural variability among them in terms of salinity, water level and substrate (Selig et al., 2007). It is this variability in lagoon systems that has led to much debate amongst ecologists on the ecological characterisation of these coastal ecosystems and to date no consensus has been reached on the ecological characterisation of lagoons (De Biasi et al., 2003). For example, regarding their geomorphology and connectivity, depending on their degree of isolation from the coastal ocean provided by the barrier coastal lagoons, can be classified as restricted, choked or leaky (Kjerfve, 1994). Salinity is also used to classify coastal lagoons in oligohaline (< 5 ppt), mesohaline (5-18 ppt), polyhaline (18-30 ppt) or mixoeuhaline (> 30 ppt) (De Wit, 2011). The term poikilohalinity is sometimes used to characterise the highly fluctuating salinity conditions that are so characteristic for many lagoons (De Wit, 2011). Tidal regime can be also considered a parameter for defining coastal lagoon classification in microtidal (< 1 m), low and high mesotidal (1-5.5 m) and macrotidal (> 5 m) (Hayes, 1979). Based on the trophic status, coastal lagoons may be hypereutrophic (> 500$gCm^{-2}yr^{-1}$), eutrophic (300 to 500 $gCm^{-2} yr^{-1}$), mesotrophic (300 to 500 $gCm^{-2} yr^{-1}$) and oligotrophic (< 100 $gCm^{-2} yr^{-1}$) (Kennish, 2015; Nixon, 1995). These are just some examples, but many other classifications exist (e.g., Haines et al., 2006; Mahapatro et al., 2013). On the other hand, socio-economic classification of coastal lagoons is a rather complex process and so far, no such schemes have been applied globally to the knowledge of the authors.

Regarding governance, the definition of "coastal lagoon" is also controversial. The EU Water Framework Directive (WFD) 2000/60/EC defines transitional waters as "bodies of surface water in the vicinity of river mouths which are partly saline in character as a result of their proximity to coastal waters, but which are substantially influenced by freshwater flow" (EU, 2000). However, this definition applies only to some coastal lagoons, e.g., those located in temperate, Mediterranean and arctic waters, whereas the formations and geography that dominate the tropics are excluded, and in general there are numerous lagoons that are not influenced by freshwater. So, for EU WFD purposes, lagoon systems are either grouped under transitional water types or coastal water types, depending on the influence of freshwater into the system, when, in fact, coastal lagoons show a coherent functioning between the different lagoon typologies, that differentiate them from estuaries and open coastal waters, sitting in reality between transitional and coastal waters (Pérez-Ruzafa et al., 2011). Similarly, the United States Environmental Protection Agency (US EPA) Aquatic Biodiversity Glossary defines a lagoon as "a shallow pond where sunlight, bacterial action, and oxygen work to purify wastewater; also used for storage of wastewater or spent nuclear fuel rods" and a "shallow body of water, often separated from the sea by coral reefs or sandbars". At the time of writing, the US EPA website contains no dedicated webpage on coastal lagoons, as it does for estuaries (https://www.epa.gov/nep) and coastal wetlands (https://www.epa.gov/wetlands). The

Australian Government's Department of Climate Change, Energy, the Environment and Water (DCCEEW) lists lagoons under wetlands together with swamps, marshes, mudflats, mangroves, coral reefs, bogs, fens and peatlands (DCCEEW, 2025). Often, no explicit management-level distinction between lagoons and other coastal or transitional water bodies is made by policy makers and environmental agencies.

In this White Paper we define coastal lagoons as ***surface water bodies that are partially isolated from an adjacent sea by a sedimentary barrier, but which nevertheless constantly or intermittently receive an influx of water from that sea*** (Barnes, 2001).

Why Coastal Lagoons Matter: Their Vital Role in Ecosystems and Communities

Due to the high variability and different definitions, the total number of coastal lagoons worldwide is not clear. However, what is evident is their high variability in size including transitional systems from small ponds < 1 km^2 to large water bodies exceeding 10,000 km^2 (Barnes, 2001). Coastal lagoons are most characteristic of regions with a tidal range of < 2 m, since large tidal ranges (> 4 m) generate powerful water movements affecting sedimentary barriers. Thus, coastal lagoons present a broad distribution and are of special relevance in continents such as America, Africa and Asia (Barnes, 2001).

The characteristics of coastal lagoons are largely defined from their configuration and geomorphological features (Pérez-Ruzafa et al., 2007a). From an ecological perspective, lagoons are characterised by a natural high spatial and temporal variability (Newton et al., 2014). They are highly productive ecosystems, typically 10-15 times more so than continental shelves (Valiela, 2015), yield a broad range of natural services (Anthony et al., 2009; Newton et al., 2018) and support high biodiversity (De Wit, 2011). Lagoon systems offer indispensable habitat for many settled or migratory species such as birds, mammals, reptiles, fish and shellfish, and in many parts of the world they are designated Ramsar sites (https://www.ramsar.org/) or, in the case of Europe, Natura 2000 sites (https://natura2000.eea.europa.eu/). They are also framed and often connected or defined by a variety of habitats such as saltmarshes, seagrass beds, mudflats, salt flats and mangroves, which are not only important as biodiversity hotspots but also play a major role as Blue Carbon stores (*cf*. Blue Carbon Initiative, 2025; Debrot et al., 2019).

Determination of the ecological quality of lagoon systems by monitoring their biological community is a useful tool to determine long-term impacts of anthropogenic activities (Crowe et al., 2000; Casal et al., 2022). In the European context, the use of biological communities to monitor water quality is promoted under EU WFD to determine the ecological status of a waterbody. An example of such an approach is the use of marine benthic macrophytes, which include seaweeds and seagrasses, and are listed in EU WFD as a "quality element" for the classification of marine coastal areas (EU, 2000). Despite the absence of a universally accepted ecological classification system for lagoons, studying their biological community provides a useful tool to monitor the ecological health of coastal lagoons.

Lagoons provide many ecological services by protecting coastal watershed areas, buffering the infrastructure from the damaging effects of storms, floods, and erosion, and others. Numerous marine species of entertaining and marketable importance spend at least a percentage of their existence phases in lagoons and neighbouring wetland habitats (Whitfield, 2011). Apart from the extraction of the living resources values, coastal lagoons are used by humans for aquaculture, renewable energy and non-renewable energy extraction (fossil fuel), biotechnology, infrastructure support (e.g., airports, marinas, shipping, maritime transport), tourism, recreation, and many other uses (Joyeux & Ward, 1998; Whitfield, 2011; Newton et al., 2014). Coastal lagoons also offer cultural services by serving as sites of spiritual and religious significance, sources of inspiration and aesthetic value, and are repositories of cultural heritage (Newton et al., 2018; Soria et al., 2022; Rodrigues-Filho et al., 2023). Even though coastal lagoons offer a diverse range of essential ecosystem services and benefits that contribute to human well-being, **the identification, classification and evaluation of these services remain complex, and unresolved challenges still exist with limited scientific literature available on the topic** (Pérez-Ruzafa et al., 2019).

Pressures Threatening Coastal Lagoons

Coastal lagoons, geologically unstable and ephemeral environments, have originated during the Holocene (~6,000-8,000 years ago) when sea level rose (Mahapataro et al., 2013) and are nowadays considered **one of the most threatened type of ecosystem in the world** (Newton et al., 2018). Coastal lagoons have long been utilised by humans, with their activities influencing lagoon processes. However, as population growth drives higher demand for resources and increases waste production, these ecosystems face a greater risk of collapse. To prevent this, social awareness must improve, and effective management strategies must be implemented (Pérez-Ruzafa et al., 2019). Due to their extreme sensitivity, these ecosystems are particularly vulnerable to human pressures, making sustainable management essential to preserving their significant socioeconomic and environmental value (Pérez-Ruzafa et al., 2019).

Given their sensitivity to sea-level fluctuations and water salinity changes, these ecosystems are also particularly affected by global climate change. Various aspects of climate change (including rising sea surface temperatures, sea-level rise, altered rainfall patterns, and more frequent and intense storms), further threaten the ecological functioning of coastal lagoons and the essential ecosystem services they provide (Suursaar et al., 2024). For example, in Bangladesh alone, 3.8 million people living on the coast were internally displaced in 2019 and 2.5 million in 2020 due to intense storms and their impacts (IDMC, 2025). Coastal lagoons are, therefore, often regarded as “sentinel systems” due to their heightened vulnerability to climate change, making them useful indicators of regional and global environmental shifts (Brito et al., 2012; Mazzilli & Christian, 2007).

Box 2. Unique systems; Three defining characteristics of coastal lagoons

Depending on their morphology, lagoons are impacted predominantly by terrestrial and/or marine influences. In lagoons with large catchment areas, terrestrial influences can be dominant but often difficult to regulate. In contrast to other coastal landforms such as estuaries and deltas, the water exchange of coastal lagoons with the open sea is more restricted, hence, they are more vulnerable to change. As a result, coastal lagoons are extremely vulnerable to human activities and pressures, which contribute to the change of the equilibrium state of these ecosystems, and many lagoons worldwide are ranked as highly impacted and altered aquatic ecosystems severed by anthropogenic intervention (Evans, 2008). Natural drivers of change include climate change (e.g., changing patterns of precipitation, sea level rise, warming), decadal climate variability (e.g., ENSO, NAO) and extreme events (e.g., storms causing coastal erosion, heat waves leading to algal blooms); while socio-economic drivers include population growth, land use change (within the lagoon and in the catchment), pollution and coastal protection infrastructure.

As a result of this complex combination of dynamic interactions of natural and socio-economic processes on different temporal and spatial scales, *coastal lagoons are considered unique ecosystems*.

We recognise three key conditions that make coastal lagoons unique (Nayak, 2014):

1. Coastal lagoons are distinguishable by their typical location at the **interface of sea and land,** acting as a unique connecting link between the two.
2. Coastal lagoons are **complex socio-ecological systems** (Almudi & Kalikoski, 2010; Benessaiah & Sengupta, 2014; Coulthard, 2008; Nayak et al., 2016; Seixas, 2002).
3. Coastal lagoons are highly interconnected systems of humans and environment, also described as **coupled human-environment systems** (Turner et al., 2003), emphasising that the two parts (human system and environmental/ biophysical system) are equally important, and they function as a coupled, interdependent, and co-evolutionary system.

Figure Box-2. *Interface of sea and land; Curonian Lagoon Spit and Baltic Sea. Image bought on Shutterstock*

On the other hand, the significant variability in the physical and chemical properties of coastal lagoons classifies them as naturally stressed environments. Species inhabiting these areas must be highly adaptable, capable of adjusting their physiology and behaviour to continuously fluctuating conditions across both spatial and temporal scales. This natural stress shares similarities with anthropogenic stress, a concept referred to as the "Estuarine Quality Paradox" (Elliott & Quintino, 2007), which complicates the detection and assessment of human-induced impacts on these ecosystems (Pérez-Ruzafa & Marcos, 2015). Determination of the ecological quality of lagoon systems by monitoring their biological community has been a traditionally useful tool to determine long-term impacts of anthropogenic activities (Crowe et al., 2000). However, **their health status, inherent sensitivity and response to change within the wider context of socio-economic and environmental pressure yet remains to be fully characterised.** At present, the biological and ecological impacts of climate change on lagoon organisms and ecosystems remain largely speculative, with limited supporting evidence (Pérez-Ruzafa et al., 2019). **Enhancing our understanding requires the study of ecological descriptors and the identification of the most reliable and suitable indicators**, which are essential for informing mitigation strategies (Pitacco et al., 2018). And, while providing an exhaustive list of relevant descriptors and suitable indicators is outside the scope of this White Paper, in the Appendix we list global aspirations and agreements for sustainability that are relevant to coastal lagoons.

The past, current and future role of Earth Observation in Coastal Lagoon Monitoring and Management

Earth Observation has evolved as a key tool for the area-wide and spatially explicit monitoring of the state of the environment beyond physical or political boundaries and at various temporal and spatial scales. In contrast to in-situ measurements, remote sensing data provide uniform information over the globe in a cost-effective way and as a result make an excellent source of data and information for global assessments. Using EO from multi-year satellite missions, it is possible to quantitatively measure various coastal lagoon geomorphological and ecological features, provide cover frequently and repetitively throughout the year(s), develop change detection techniques, and provide useful information to be used in models and integrated into Geographical Information Systems (GIS) (Fitoka & Keramitsoglou, 2008) and decision-making tools.

Through EO, one can retrieve estimates of a wide array of geophysical and biochemical parameters for water, land and atmosphere. Acquiring information from this triangle of sources is particularly important in coastal lagoon areas (Ramesh et al., 2015), which are not only the interface of sea and land but are also threatened by climate change driven changes manifested as extreme events facing lagoons on all three fronts: water-, land- and atmospheric (or climate)-front. In the following sections, we provide the historical context and state-of-the-art with respect to satellite sensors suitable for aquatic remote sensing, present the main challenges and gaps in the use of EO for coastal lagoon monitoring and mention a few of the most prominent and relevant initiatives with strong potential to play key roles in sustainable coastal lagoon management.

Historical context and state-of-the-art

EO is an increasingly utilised tool for obtaining information about water bodies. Although the use of EO in aquatic studies has significantly increased in recent years, its origins date back several decades. In 1971, the Landsat 1 satellite, the first satellite dedicated to EO, was launched. Despite its limited technical capabilities, some researchers were able to estimate certain parameters of water bodies (Gervan & Marshall, 1977). A few years later, in 1978, the Nimbus 7 satellite was launched with the Coastal Zone Color Scanner (CZCS) onboard, the first sensor dedicated to the global observation of coastal surface waters. These early data demonstrated the relevance of this type of information and paved the way for the development of numerous and diverse sensors, resulting in a vast array of data related to water bodies. For example, optical sensors provide information on the "colour" of water and its constituents (chlorophyll, phycocyanin, turbidity, *etc.*), radar sensors (L-band) estimate parameters like salinity, and thermal infrared sensors supply temperature data.

Along this line, sensors such as SeaWiFS, MODIS, MERIS, and more recently VIIRS have globally recorded ocean data, but their technical characteristics, particularly their spatial resolution, limit their utility for many coastal or inland water bodies. For this reason, numerous studies have had to rely on satellites and sensors primarily designed to observe terrestrial systems, such as the Landsat series (Kutser et al., 2012; Luis et al., 2019) or SPOT (Dekker et al., 2002; Rotta et al., 2016). One of the most successful and long-term missions by NASA, the Landsat series of satellites are often used in water applications, e.g., to map water quality in lakes (see NASA STREAM) and coastal regions (e.g., Chacko & Jayaram, 2024; Luis et al., 2019; Niroumand-Jadidi et al., 2022). In addition, the very successful and versatile Copernicus Sentinel series, a productive collaboration between the European Space Agency and European Commission, has put into orbit four satellites widely used in environmental applications and especially aquatic mapping; Sentinel-2A/B MSI and Sentinel-3A/B OLCI. Sentinel-2 offers improved spectral and radiometric resolutions, as well as a shorter revisit time compared to satellites like SPOT or Landsat, and higher spatial resolution compared to Sentinel-3 or other oceanic sensors. Although Sentinel-2 was also initially designed for terrestrial environments, its potential for studying coastal and inland water bodies has been demonstrated in various studies (e.g., Ansper & Alikas, 2019; Hedley et al., 2018; Kong et al., 2025; Meng et al., 2024; Salls et al., 2024; Toming et al., 2016). The OLCI sensor onboard the Sentinel-3 satellite was designed for oceanic waters and provides data at a spatial resolution comparable to MERIS (300 m), offering a greater number of spectral bands and a much shorter revisit time. The same satellite can also record temperature data through the SLSTR sensor that carries onboard. All these new (freely accessible) datasets, combined with their long-existing data series, make the current moment particularly relevant for the development of new applications and the generation of new information and services related to water bodies.

Another aspect that has been gaining importance among the international community is the development of hyperspectral sensors. Hyperspectral satellite missions could be considered the next milestone in the remote sensing of water bodies, with impacts on many applications such as benthic mapping, phytoplankton ecology, or the detection of Harmful Algal Blooms (HABs). After some hyperspectral sensors like Hyperion onboard the EO-1 satellite, ESA's CHRIS Proba, or the Hyperspectral Imager for the Coastal Ocean (HICO), most of which were experimental, the Italian Space Agency launched the PRISMA satellite in 2019. One of PRISMA's operational modes is to collect hyperspectral and panchromatic data upon user request. Since then, the ever growing field of satellite remote sensing has been enhanced by the launch of several space-borne hyperspectral sensors, such as the German hyperspectral satellite mission Environmental Mapping and Analysis Program, EnMAP (launched 2022), covering several applications including water availability and quality, and NASA’s Plankton, Aerosol, Cloud ocean ecosystem, PACE (launched 2024), aimed mainly at ocean colour applications and carrying the Ocean Color Instrument (OCI). OCI is of enormous relevance for providing new data on global aquatic ecology and biogeochemistry, as well as its sensitivity to environmental changes (Werdell et al., 2019). However, its spatial resolution of 1 km could be a limitation factor in some small/medium coastal lagoons. These new instruments are responding to the remote sensing community’s long-standing requests and complement older, still operational, missions such as the high-resolution optical imaging constellation of the French national space agency’s (CNES) twin satellites Pleiades-1A (launched 2011) and Pleiades-1B (launched 2012). Planned missions include the Copernicus Hyperspectral Imaging Mission for the Environment (CHIME) (expected launch date 2028).

Several commercial entities are adding to this suite of satellite hyperspectral missions, a lot covering themes with direct or indirect relevance to coastal lagoon management. Hyperspectral optical sensors cover methane emission detection (e.g., Planet Tanager), land and aquatic feature classification (e.g., WorldView series), urban planning, land use and agricultural applications (e.g., SuperView). Hyperspectral thermal sensors are suitable for surface temperature measurements, fire detection, thermal stress, energy efficiency, heatwaves, and other urban, infrastructure and agricultural applications (e.g., constellr SkyBee, HotSat, OroraTech FOREST), Finally, hyperspectral SAR sensors are used for maritime and port monitoring, deforestation, sea ice, and oil spills (e.g., ICEYE), land surface topography, sea ice cover and type, snow cover, glacier motion, soil type (e.g., COSMO-SkyMed), as well as military and civil applications (e.g., PAZ).

And while the number of hyperspectral/high resolution satellites is growing, the next generation of multispectral/medium-resolution satellites is also in the making. With tens of use cases and hundreds of publications using OLCI, MSI and Landsat data to show the user community's support (and need) for continuation, the next generation is underway, with Sentinel-2C MSI having successfully launched (September 2024), Sentinel-3C being provisionally set for late 2026 and Landsat Next (constellation of three super-spectral satellites) expected to launch in late 2030/early 2031. While the Sentinels offer continuation with similar technical capabilities and configurations, Landsat Next differs. The Landsat Next triplet of satellites will provide improved revisit capability, and spatial and spectral resolutions compared to its predecessors (Landsat 8 and Landsat 9). Notably, Landsat Next will measure in 15 additional wavebands than the currently operational Landsat 8 and Landsat 9 missions. While the 11 original wavebands will remain for continuity, five new wavebands are added with similar spatial and spectral characteristics to Sentinel-2 MSI enabling better data synergy and fusion, while the other ten new spectral wavebands have responded to user needs and support emerging applications.

Earth Observation for coastal lagoon monitoring

The high dynamics and optical complexity of coastal areas in general and coastal lagoons in particular represent a major challenge in designing a programme to adequately monitor and analyse these environments. Field programmes consisting of periodic in-situ measurements, using traditional field instruments and sampling protocols from boats, are most often ineffective in capturing the range and variability of many coastal processes (Finkl & Makowski, 2014). Therefore, this approach frequently results in under-sampling in both space and time. EO techniques represent a unique approach to gain frequent synoptic data to address the complex nature of many coastal processes (e.g., Cavalli, 2024; Kutser et al., 2020). The use of remote sensing data along with existing in-situ approaches is crucial to advance our knowledge about the global status of coastal lagoons as well as to understand their role in coastal processes.

While existing satellite sensors offer suitable spatial resolution, their spectral and temporal resolution limits their application for studying certain processes in coastal or inland waters. Consequently, although research on remote sensing of oceanic, coastal and inland waters has been conducted for nearly the same amount of time, oceanic remote sensing has been adopted operationally, while progress in coastal and inland water remote sensing has been more limited (IOCCG, 2018). The use of EO for coastal and inland waters faces many challenges related to the science of extracting physical and biochemical properties from these optically complex waters (i.e., with varying levels of optically active constituents such as phytoplankton, suspended sediments and coloured dissolved organic matter, giving water a wide range of colours depending on the relative confrontations of each). Furthermore, research in this field has suffered from a lack of funding, infrastructure, and mechanisms needed to coordinate research efforts within what has historically been a rather fragmented community (Mouw et al., 2015; Palmer et al., 2015). This trend seems to be changing in recent years, and the observation of water bodies, especially coastal and inland waters, is receiving special attention from the international community. Also, the use of EO in coastal lagoon applications has considerably increased in recent years (Box 3) but remains relatively low in comparison with other environments such as coastal waters or lakes.

Box 3. Coastal lagoons remain under-studied in literature

A recent search on Scopus, a widely recognised bibliographic database of academic research, using "coastal lagoons" in the article title, abstract and keywords and using the filter by year "up to 2024" and by "Planetary and Earth Science" where remote sensing is frequently included, returns a result of 6,295 documents. However, the same search using "lakes" instead of "coastal lagoons" results in 100,174 documents. These searches are quite generalist and have probably overestimated the values but indicate how remote sensing remains underexploited in coastal lagoons.

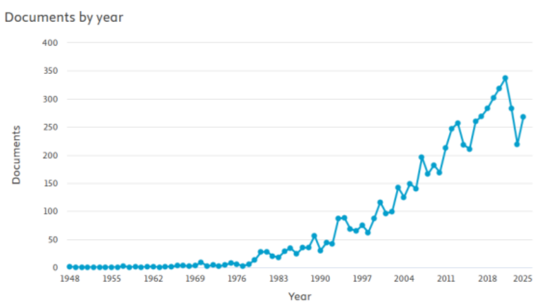

Figure Box-3. *Search in Scopus using the terms "coastal AND lagoons" in article title, abstract and keywords, filtered by "Planetary and Earth Sciences" resulted in 6,295 documents between 1948 (the first published document) and 2024. The number of documents increases exponentially with time.*

Such published studies tend to be based on short-term projects without temporal continuity and are spatially limited to local study areas. As in the situation of inland waters reported by Palmer et al. (2015), *the fragmented nature of funding has impeded the exchange of skills and expertise across the community and made it more challenging to facilitate share use of in-situ data and other resources necessary to address some of the key challenges from a global perspective*. Differences in the methods and protocols between research groups, regions and nations further constraints a homogenous and consistent assessment of coastal waters in general, and of coastal lagoons in particular, as well as their monitoring at different scales (e.g., Carvalho et al., 2011; Palmer et al., 2015; Tyler et al., 2016).

We conclude that **our knowledge of the global status of coastal lagoons and their responses to environmental and anthropogenic change remains incomplete** and, therefore, there is an urgent need to increase our understanding of these valuable environments.

More work is needed to integrate EO data in coastal lagoon management. The health of a coastal lagoon and its ability to deliver ecosystem services is inherently related to its ability to dynamically adjust to the changes it is exposed to. This ability, however, is hampered by anthropogenic modifications of the coastal lagoon. Beyond individual environmental and ecological variables, multi-source satellite EO information could be used to derive indicators and indices for the assessment of the status and future threats on coastal lagoon systems. Nowadays, there is a high number of potential sensors and platforms that could be used for coastal lagoon applications (Figure 2) covering different spatial and temporal resolutions, but further research is needed to evaluate their accuracy and synergies in coastal lagoon applications.

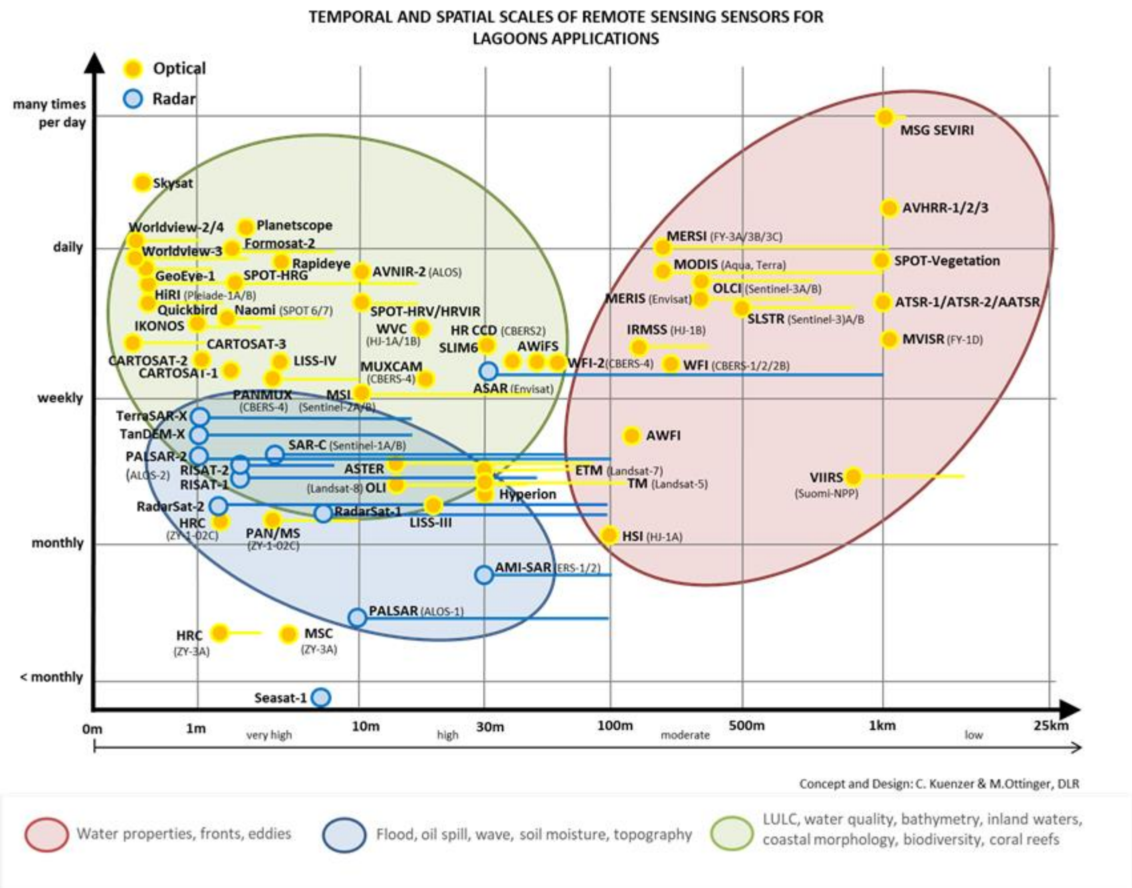

Figure 2. *There are numerous remote sensing instruments that are suitable for lagoon studies.*

Challenges and Gaps of EO for Coastal Lagoon Monitoring

Our knowledge of **the number and global status of coastal lagoons as well as their responses to environmental change remains incomplete**. Even though the use of spaceborne and airborne EO data is now becoming well established in the provision of information on marine and inland waters, coordination of research and expertise from multiple geographic locations is required to maximise the usage and impact of these EO resources in coastal lagoons, especially if we take into account that coastal lagoons are often small in size and dispersed. *Only if reliable and up to date information on these highly dynamic environments is available, well-informed decisions for their sustainable management and protection can be adopted.*

While efforts are ongoing across the scientific community to overcome several of the methodological, technological challenges and knowledge gaps in coastal lagoon remote sensing, it is not the purpose of this White Paper to review and present those. However, we briefly present below the most common limitations.

Methodological challenges

There exist several methodological challenges when employing EO in coastal lagoon monitoring. The include:

- ***Atmospheric correction*** is more challenging over optically complex waters, such as lagoons. At satellite altitude, approximately 90% of the sensor-measured signal corresponds to atmospheric and surface effects (Gordon & Morel, 1983), making atmospheric correction a crucial step in aquatic applications, where the signal returning to the sensor is relatively weak.
- ***Bottom reflectance*** can affect satellite imagery in shallow, clear waters and must be removed, if the purpose of the analysis is the map the water surface or column and not the benthic habitats or sediments.
- ***Adjacency effects*** from surrounding (relatively brighter) land that contributes reflected light and, thus, "contaminating" the information from water pixels must be accounted for.
- ***Sunglint***, a bright effect caused by specular reflection of sunlight on the water surface when radiation is reflected at the same angle as the viewing angle of the sensor, "contaminates" satellite imagery and must be removed or accounted for.
- ***Cloud cover.*** Optical and thermal remote sensing of water bodies is limited by cloud cover, which exhibits seasonal, interannual and latitudinal variability.
- ***Bio-optical algorithm accuracy*** depends on the optical complexity of the water (i.e., the relevant concentration of optically active water constituents such as phytoplankton, particulate organic detritus, suspended sediments and coloured dissolved organic matter) and there is currently not one-fits-all model. Instead, methods like classifying water pixels in "optical water types" helps identify the most suitable algorithm (or suite of algorithms) per pixel.
- ***Validation*** of EO maps depends on availability of concurrent, suitable and reliable in-situ data, which is rarely the case. This problem can be further amplified in large cross-border lagoons, where in-situ sampling efforts are constrained not only by the vast geographical extent but also by disparities in monitoring protocols, equipment, and data-sharing practices between neighbouring jurisdictions.

- ***Effort investment and funding availability***. As argued by Palmer et al. (2015), fragmented research efforts and limited funding have hindered knowledge exchange within the coastal lagoon research community. Many studies are based on short-term projects, lacking both temporal continuity and broad spatial coverage.
- ***Differences in methods and protocols*** across research groups, regions, and nations further restrict the development of a consistent and standardised approach to assessing and monitoring coastal waters, including coastal lagoons (e.g., Carvalho et al., 2011; Palmer et al., 2015; Tyler et al., 2016).

For the above reasons, coastal waters have more demanding requirements for the satellite instrument's spectral and spatial resolution, revisit time and radiometric sensitivity, atmospheric correction accuracy and water constituent retrieval algorithms (IOCCG, 2000), which still need to be successfully tackled. Solutions used for the open ocean waters research cannot be simply utilised for the coastal environments.

Technological challenges

The technological challenges associated with effective and successful coastal lagoon monitoring include:

- ***Multi-platform monitoring.*** It is now widely acknowledged that to monitor coastal waters with the necessary sampling frequency in space and time, it is essential to complement conventional in-situ analysis methods with the data derived from remote sensing technology, such as satellites, airborne, ship or station-based innovative high resolution optical sensors (e.g., Volpe et al., 2012). However, this requires increased effort for monitoring and analysis and leads to higher overall costs. It also requires multidisciplinary expertise.
- ***Sensor specifications***. While the current generation of satellite sensors successfully used for water body monitoring (e.g., Landsat 9, Sentinel-2 and Sentinel-3) have increased signal-to-noise ratio and spatial, spectral and radiometric resolutions, these may still not be sufficient for smaller water bodies, or phenomena that take place at shorter time scales (see Figure 2). The problem of infrequent revisit times is partly tackled by constellations of same-sensor satellites, i.e., satellites in tandem orbits, that effectively decrease revisit times, but these data still require accurate intercalibration before they can be used for the same analysis.
- ***Computing technologies***. A further challenge with exploiting long-time series EO data is access and analysis, particularly where the data volumes are in the order of gigabytes or terabytes. To deal with so-called "Big Data", it is possible to use web-based analysis software using open standards from the Open Geospatial Consortium for serving images, data arrays and single point or vector data. Such

software allows cloud-based analysis and users can download the results instead of requiring downloading raw data. One such example is the ESA CCI Ocean Colour web portal that allows viewing of time series of the entire multi-sensor, debiased dataset (1997-to date) for user-defined regions, production of Hovmoller plots, animations and data extractions along transects or for comparison with in-situ data.

- ***Data expertise***. As the datasets become larger and the analysis methodologies more complex (e.g., use of programming languages for environmental research, methods like multi-sensor data fusion, Machine Learning and Artificial Intelligence), scientists and researchers need to acquire more skills to be able to analyse large datasets. However, several countries are still hindered by the lack of expertise or facilities (European Commission, 2015). Often, users interested in EO products face difficulties in finding suitable data and incorporating them into their applications and can be faced with the challenge of technology laden with confusing terminology, data and methods of processing and analysis (Kachelriess et al., 2014; Miller et al., 2005).

Data and knowledge gaps

Key high-level data and knowledge gaps for coastal lagoon monitoring include:

- ***Lack of dedicated databases.*** Although large scale initiatives exist providing EO-based data for oceans and regional seas (e.g., EuroGOOS, Copernicus Marine, ESA CCI, GlobColour), and lakes (e.g., Copernicus Land Monitoring Service, GlaSS, GloboLakes), coastal lagoons are not truly represented, even though some of these initiatives include a limited number of coastal lagoons.
- ***Fragmented data collection.*** The distinct separation between research, management, and public education communities has restricted the transfer of key space-based technologies into resource management and education. These limitations have been recognised also by the European Commission (European Commission, 2015) indicating that the current process of collecting, storing and distributing EO data remains fragmented, incomplete or redundant.
- ***Lack of standards and common nomenclature.*** The variety of ways in which data are measured, recorded and analysed represents a barrier to their integration (European Commission, 2015), including lack of common nomenclature and metadata standards across disciplines. Facilitating interdisciplinary analysis of the existing work and inter-comparison of data will produce new perspectives on the applications of EO to coastal areas and foster the generation of optimised protocols and databases.

The existing gaps in knowledge and lack of comparability of the data are not only a barrier for scientists, but also for those dealing directly with the natural resources (for example agriculture, fisheries, nature conservation) and decision-makers in charge of protecting biodiversity or shaping environmental policies. They require the data in digestible format, as well as more standardised data collection and analysis. These challenges are complex, interrelated, cross-border in nature and interdependent at the global scale, and therefore coordination is essential to avoid duplication of efforts and to reduce the observational gaps. This coordination will promote new opportunities for businesses across the globe to develop value-added services as well as facilitate the development of strategic partnerships to jointly address the coastal challenges.

Integrated sustainability at global and local scales

Pressures in coastal lagoons do not operate independently and need to be considered together but their interactions are not necessarily linear. Consequently, holistic monitoring and management practices are pertinent, aiming to understand the complex links that exist between the social and ecological parts of lagoons, in relation to their setting and wider landscape. Such practices should rely on integration of different data sources including Earth observation, ground measurements, local knowledge and modelled data in a "triangular approach" such is the one adopted by the United Nations Environment Programme (UNEP) World Water Quality Alliance (WWQA) (2021). They should also consider **global** aspirations and agreements for sustainability, in addition to **local** and **national** management needs and strategies, integrating them with local and national strategies to ensure a comprehensive and effective approach. Relevant goals, priorities and targets stemming from global aspirations and agreements are listed in the Appendix. In the following section, existing initiatives, programmes, concepts, frameworks and research infrastructures that are relevant and key to exploiting towards holistic sustainable coastal lagoon management are presented. While the authors acknowledge that this list is not exhaustive, it serves as indicator of the significant programmatic, methodological and technological progress in recent decades.

Existing initiatives

The *UN Global Sustainable Development Report 2019-The Future is Now: Science for Achieving Sustainable Development* highlighted that, despite early efforts, progress toward most SDG targets remain off track (Estoque, 2020). It has also been unclear how much the environmental effects of economic activities vary between countries and affect SDG-target achievement (Han et al., 2024). Recognising the potential of Earth Observation for SDG monitoring, the Group on Earth Observations (GEO) launched the *Earth Observations in Service of the 2030 Agenda for Sustainable Development (EO4SDG)* initiative in 2016. Through EO4SDG, the full potential of remote sensing has been leveraged globally to enhance sustainability monitoring and decision-making. Other such initiatives in support of SDG reporting, include the UN Environment Programme (UNEP) Freshwater Ecosystems Explorer that provide open-access geospatial data and products to support decision making at national, sub-national, and basin level on freshwater ecosystems (including coastal lagoons), towards SDG Indicator 6.6.1 reporting. In 2024, the UNEP World Water Quality Alliance funded a project that developed an EO-based indicator to support Level 2 reporting of the SDG Indicator 6.3.2 based on EU Copernicus Land Monitoring Service (CLMS) Lake Water Quality (LWQ) data from Sentinel-3 (also covering some of the world's largest coastal lagoons).

Recognising the importance of ecosystem assessment in sustainable development efforts, the European Commission introduced the *EU 2020 Biodiversity Strategy* in 2011, emphasising the need for comprehensive mapping and evaluation of ecosystems and their services. This led to the establishment of the *Mapping and Assessment of Ecosystems and their Services (MAES)* initiative, which provides a structured approach for ecosystem assessment at multiple scales. However, effectively mapping these services remains a complex task, especially in complex and dynamic environments such as coastal lagoons. As efforts to enhance sustainability monitoring continue - such as those facilitated by Earth Observation initiatives - integrating ecosystem assessments into policy and decision-making frameworks becomes increasingly vital.

International programmes, concepts and frameworks

International regulatory frameworks, such as the *EU WFD*, increasingly require expanded coverage and more frequent monitoring of coastal lagoon ecosystems. As mentioned already, under the WFD, coastal lagoons are classified as either "transitional waters" or "coastal waters," necessitating specific and in some cases different monitoring tools to evaluate their ecological status. Given their significant environmental, social and economic value, it is crucial to implement strategies that **balance human activities with conservation efforts, safeguarding biodiversity, natural heritage, and socio-economic benefits for future generations** (Gaertner-Mazouni & De Wit, 2012). However, challenges in developing effective management plans highlight the need to reassess the role of the scientific community, as suggested by previous studies (e.g., Dobbs et al., 2011; Lester et al., 2010). In this context, *adaptive management* has emerged as a promising approach, as demonstrated in the successful management of the Great Barrier Reef in Australia (Dobbs et al., 2011). This type of strategy emphasises the continuous review and adjustment of management practices to respond to evolving environmental conditions and challenges.

In recent years, nature-based solutions (NbS) implemented at local and regional scales have gained recognition as an effective means of addressing various societal challenges, such as biodiversity decline and the effects of climate change. Marine and coastal "blue NbS" initiatives encompass conservation efforts, restoration activities, and other sustainable management strategies that align with specific criteria (IUCN, 2020). Despite the significant potential of NbS for marine and coastal environments, their implementation has progressed more slowly compared to terrestrial and urban areas (O'Leary et al., 2023; Pérez et al., 2024). This delay is partly due to a lack of tools and resources to assist practitioners and decision-makers in planning effective interventions (Pérez et al., 2024). While recent advancements have addressed some challenges and provide some tools for their effective implementation (Casal et al., 2025), overcoming the remaining barriers to blue NbS adoption will require a **collaborative approach** that brings together researchers, practitioners, policymakers, industries, and local communities (O'Leary et al., 2023; 2024). Such coordination and interdisciplinary efforts are particularly crucial in coastal lagoons, where varied stakeholder interests and multiple human activities intersect with the dynamic and heterogeneous nature of these ecosystems.

There are also operational EO products and processing chains available for open ocean and coastal environments such as the European Copernicus Marine Environment Monitoring Service (CMEMS) as well as research and development programmes such as the ESA Climate Change Initiative (CCI) Ocean Colour that aim at producing long-time essential climate variables (ECVs). The production of these ECVs often relies on combining data from multiple satellite missions, each with different characteristics. Both initiatives cover some coastal lagoons globally, while CMEMS was recently expanded to include 100-m spatial resolution coastal products in European Seas based on Sentinel-2 MSI data, including chlorophyll, turbidity and suspended matter.

Other programmes covering inland waters such as ESA CCI Lakes and Copernicus Land Monitoring Service (CLMS) are focussed on global water quality products in freshwater lakes but cover some coastal lagoons globally too. ESA CCI Lakes and CLMS produce water quality products of relevance using specific approaches for the (optically) complex nature of inland and some transitional (estuaries and coastal lagoons) waters using medium spatial resolution data from ESA MERIS (300 m; 2002-2012) and ESA Sentinel-3 OLCI (300 m, 2016-to date), and higher spatial resolution data from ESA Sentinel-2 MSI (100 m, 2015-to date). The CLMS service is currently producing 10-day averages (dekads) of chlorophyll-a, trophic status, turbidity, total suspended matter, floating cyanobacteria presence probability and reflectance in "near-real time" (NRT), which are available 3 days (OLCI) or 4 days (MSI) after the last acquisition date. Technically, it is relatively straightforward to add in additional coverage over coastal lagoons to this provision, but validation of products will require in-situ measurements; traditionally a main drawback in the operationalisation of EO.

Relevant research infrastructures

Another recent innovative development is aiming to create a near-real time virtual representation of the coastal and open ocean. This new initiative called Digital Twin Ocean (DTO) combines geospatial data, artificial intelligence, and advanced modelling to become a consistent, high-resolution, multi-dimensional observatory of the global ocean. DTO is compatible with ESA, EUMETSAT and ECMWF's DestinE architecture of Digital Twins, and supports EU's 2030 Digital Compass strategy for the 2021-2030 decade and EU's 2020 Green Deal with the goal that EU achieves climate neutrality by 2050. As an extension to DTO, the EU-funded project IDEATION is preparing the pathway for integrating information pertaining to inland waters (rivers, lakes, reservoirs, wetlands, snow, and ice) in DTO. It remains to be seen if either initiative will cover transitional water bodies like coastal lagoons.

Additionally, the recently established European Research Infrastructure Consortium (ERIC) DANUBIUS-ERIC, which is based on 10 years of operations of DANUBIUS-RI (Research Infrastructure) "International Centre for Advanced Science on River-Sea Systems", covers aspects of coastal lagoons systems in its wider River-Sea-Systems approach, comprising river catchments, estuaries/deltas, lagoons and coastal seas. DANUBIUS-ERIC provides knowledge (data and training) and infrastructure in support of understanding and managing complex dynamics of river-sea systems and focusses on science-based solutions for a more resilient and sustainable future. Another such infrastructure, LifeWatch ERIC, supports biodiversity and ecosystem research in several ecosystems including coastal lagoons, through open and diverse data, advanced modelling, and open science clouds. LifeWatch ERIC aims to enable advancements in ecological science and ensure societies are better equipped to address planetary challenges.

Conclusions

Despite their ecological, economic and social importance, the scientific study of coastal lagoons remains behind oceanic and inland waters while most coastal lagoons worldwide have been poorly studied to date. One reason for that is that the scientific community focused on coastal lagoons has historically been fragmented, only beginning to come together in the latter decades of the 20th century (Newton et al., 2018). In addition, it is widely recognised that holistic approaches for coastal lagoon (sustainable) management need to rely on multi-source, multi-platform and multi-information integration. This means not only benefiting from the complementarity of in-situ, modelled and satellite data, but calls for a need to look beyond the ecological system itself, by adequately characterising the socio-economic system too. Identifying the most suitable parameters and indicators to describe the socio-ecological system, and sourcing complete and reliable data to retrieve those is the single most challenging aspect of a holistic management strategy developer. Nevertheless, we find ourselves at the foreground of technological developments, the availability of multiple global and regional open-access databases and the recognition that we must think at global scales but apply local solutions. This opens the door for innovation and novelty that are yet to be realised.

EO is a field that has exponentially evolved in the last decades. New satellites with improved technological capabilities for coastal lagoons have been launched (e.g., Sentinel-2 MSI, new platforms (e.g., UAV) have been developed and new powerful analytical techniques such as the artificial intelligence have burst in to revolutionise the analytical power. All these aspects together with the long-term series of data already available (e.g., Landsat Mission since the 70s) makes the current moment of special relevance to advance towards a holistic approach for coastal lagoon management.

However, effectively and sustainably managing coastal lagoons presents significant difficulties, not only due to existing gaps in scientific understanding but also because of the diverse range of stakeholders, the intricate social and administrative frameworks, and the division of responsibilities, which vary across countries and regions (Pérez-Ruzafa and Marcos, 2008). The future of coastal lagoons depends on addressing both current and emerging challenges while implementing effective strategies to identify, accurately describe, monitor and mitigate the most pressing issues affecting these ecosystems and to manage them correctly within a framework of sustainability and blue economy. Preserving coastal lagoons is vital, given their ecological significance and the essential ecosystem services they provide to support human well-being. To achieve this, **a holistic management approach is necessary, integrating the expertise of economists, ecologists, and environmental scientists to comprehensively evaluate these socio-ecological systems and their services** (Barbier et al., 2011).

Towards holistic coastal lagoon management

With these considerations in mind, the Lagoons for Life initiative composed of diverse-background scientists and stakeholders connected to coastal lagoons, puts forward the following actions to enhance and empower the use of EO in the monitoring and management of coastal lagoons supporting the sustainability of the invaluable ecosystem services they provide:

- ***Multi- and inter-disciplinary networking.*** Collaboration across disciplines is crucial for gathering diverse data types and expertise to enhance the understanding of coastal lagoons. Establishing standardised protocols ensures data comparability, reliability, and broad applicability of EO data for coastal lagoon monitoring and management.
- ***Promotion (visibility) of EO products for coastal lagoons.*** Increasing the visibility of remote sensing advantages for coastal lagoons helps stakeholders, policymakers, and researchers leverage these tools for better conservation, monitoring, and sustainable management. Showcasing successful applications can drive adoption and funding support.

- ***EO to better quantify the number of lagoons worldwide.*** EO technologies offer a systematic approach to identifying and mapping coastal lagoons on a global scale. Improved quantification enhances scientific understanding, supports conservation efforts, and aids in the development of global environmental policies.

- ***Validation and adjustment of EO algorithms for coastal lagoons.*** Developing and refining EO algorithms ensures more precise monitoring of coastal lagoons, particularly with the integration of new sensors. Testing these algorithms for various applications enhances data accuracy and usability for environmental assessments.

- ***Creation of global initiatives for coastal lagoons.*** Initiatives like ESA's Climate Change Initiative for lakes (ESA CCI Lakes), and operational services such as the Copernicus Marine Environment Service and Copernicus Land Monitoring Service can be expanded to intentionally and fully cover coastal lagoons, fostering large-scale and coordinated research efforts.

- ***Development of lagoons-specific vulnerability indices, indicators and multi-risk assessment frameworks*** to better understand how cumulative impacts (anthropogenic, natural and climate change) affect coastal lagoons.

- ***Support for environmental policies and international goals.*** EO data and scientific research play a key role in informing and supporting environmental regulations, such as the UN Sustainable Development Goals (SDGs) and national policies. Effective implementation requires data-driven decision-making and continuous monitoring.

- ***Citizen science for validation and calibration of EO Products.*** Engaging local communities and citizen scientists in data collection enhances the calibration and validation of EO products. This participatory approach improves data accuracy, promotes awareness, and fosters public engagement in scientific research.

- ***Knowledge transfer to countries with limited resources.*** Providing technical training and expertise in EO applications empowers researchers and decision-makers in resource-limited countries. Capacity-building initiatives, including workshops, collaborative projects, and knowledge-sharing networks, ensure these nations take full advantage of remote sensing data, maximising the value of investments in satellite missions.

- ***Funding opportunities and fellowships for coastal lagoon research.*** Dedicated funding calls are essential for advancing coastal lagoon research. Fellowships and grants (e.g., ESA Living Planet Programme, NASA Fellowships programme) encourage innovation, support early-career researchers, and sustain long-term monitoring and analysis.

References

Almudi, T., & Kalikoski, D. (2010). Traditional fisherfolk and no-take protected areas: The Peixe Lagoon National Park dilemma. *Ocean and Coastal Management, 53,* 225–233. https://doi.org/10.1016/j.ocecoaman.2010.04.005

Alongi, D.M. (1998). *Coastal ecosystem processes*. Florida: CRC Press.

Ansper, A., & Alikas, K. (2019). Retrieval of Chlorophyll-a from Sentinel 2 MSI data for the European Union Water Framework Directive Reporting Purposes. *Remote Sensing*, *11*(1), 64. https://doi.org/10.3390/rs11010064

Anthony, A., Atwood, J., August, P., Byron, C., Cobb, S., Foster, C., Fry, C., Gold, A., Hagos, K., Heffner, L., Kellogg, D.Q., Lellis-Dibble, K., Opaluch, J.J., Oviatt, C., Pfeiffer-Herbert, A., Rohr, N., Smith, L., Smythe, T., Swift J., & Vinhateiro, N. (2009). Coastal lagoons and climate change: ecological and social ramifications in U.S. Atlantic and Gulf coast ecosystems. *Ecology and Society*, *14*(1), 8. https://www.jstor.org/stable/26268055

Barbier, E.B. (2012). Progress and challenges in valuing coastal and marine ecosystem services. *Review of Environmental Economics and Policy*, *6*(1), 1-167.

Barnes, R.S.K. (1980). *Coastal Lagoons.* Cambridge: Cambridge University Press. 106 pp.

Barnes, R.S.K. (2001). Lagoons. In: Steele, J.H. (Ed.), *Encyclopedia of Ocean Sciences. Academic Press:* 1427-1438. https://doi.org/10.1006/rwos.2001.0091

Benessaiah, K., & Sengupta, R. (2014). How is shrimp aquaculture transforming coastal livelihoods and lagoons in Estero Real, Nicaragua? The need to integrate social–ecological research and ecosystem-based approaches. *Environmental Management, 54*(2), 162-179.

Berkes, F., & Folke, C. (Eds.). (1998). *Linking social and ecological systems: Management practices and social mechanisms for building resilience.* Cambridge: Cambridge University Press.

Blue Carbon Initiative (2025). [Accessed online May 2025: https://www.thebluecarboninitiative.org/]

Brito, A.C., Newton, A., Tett, P., & Fernandes, T.F. (2012). How will shallow coastal lagoons respond to climate change? A modelling investigation. *Estuarine, Coastal and Shelf Science, 112*, 98-104.

Carvalho, L., Ferguson, C.A., Scott, E.M., Codd, G., Davies, P.S., & Tyler, A.N. (2011). Cyanobacterial blooms: statistical models describing risk factors for national-scale lake assessment and lake management. *Sci. Total Environ., 409*, 5353-5358.

Casal, G. (2022). Assessment of Sentinel-2 to monitor highly dynamic small water bodies: The case of Louro lagoon (Galicia, NW Spain). *Oceanologia, 64*(1), 88-102.

Casal, G., Fonseca, C., Allegri, E., Bianconi, A., Boyd, E., Cornet, C.C., de Juan, S., Espinoza Córdova, F., Furlan, E., Gil, A., Krause, T., Maréchal, J.P., McCarthy, T., Özkiper, O., Pérez, G., Pham, H.V., Roberts, C., Simide, R., Simeoni, C., Taylor, D., Tiengo, R., Trégarot, E., Uchôa, J., & O'Leary, B.C. (2025). Informing implementation of Nature based Solutions in marine and coastal environments: the MaCoBioS Blue NBS Toolbox. *One Ecosystem, 10*, e149010. https://doi.org/10.3897/oneeco.10.e149010

Cavalli, R.M. (2024). Remote Data for Mapping and Monitoring Coastal Phenomena and Parameters: A Systematic Review. *Remote Sens., 16*, 446.

Chacko, N., & Jayaram, C. (2025). Assessing coastal water quality along Odisha using Landsat-8: Insights into seasonal and spatial variability. *J. Earth Syst. Sci.*, *134*, 79. https://doi.org/10.1007/s12040-025-02543-z

Cosby, A.G., Lebakula, V., Smith, C.N., Wanik, D.W>, Bergene, K., Rose, A.N., Swanson, D., & Bloom, D.E. (2024). Accelerating growth of human coastal populations at the global and continent levels: 2000–2018. *Scientific Reports, 14*, 22489. https://doi.org/10.1038/s41598-024-73287-x

Costanza, R., Cleveland, C., & Perrings, C. (Eds.) (1997). *The Development of Ecological Economics*. London: Edwin Elgar.

Coulthard, S. (2008). Adapting to environmental change in artisanal fisheries – Insights from a South Indian lagoon. *Global Environmental Change, 18*(3), 479-489.

Crooks, S., & Turner, R.K. (1999). Integrated coastal management: sustaining estuarine natural resources. In: Nedwell, D.B. & Raffaelli, D.G. (Eds.), *Estuaries: Advances in Ecological Research*, *29*. New York: Academic Press, pp. 241–289.

Crowe, T.P., Thompson, R.C., Bray, S., & Hawking, S.J. (2000). Impacts of anthropogenic stress on rocky intertidal communities. *Journal of Aquatic Ecosystem Stress and Recovery*, *7*, 273-297.

DCCEEW (2025). Department of Climate Change, Energy, the Environment and Water, Australian Government [Accessed online May 2025: https://www.dcceew.gov.au/water/wetlands/about]

De Biasi, A.M, Benedetti-Cecchi, L., Pacciardi, L., Maggi, E., Vaselli, S., & Bertocci, L. (2003). Spatial heterogeneity in the distribution of plants and benthic invertebrates in the lagoon of Orbetello (Italy). *Oceanologica Acta, 26*, 39-46.

De Liz-Arcari, A. (2022). Remote Sensing of Wastewater Contamination in Coastal Areas: A Case Study of Conceição Lagoon, Brazil, University of Twente Student Thesis [Accessed online May 2025: https://essay.utwente.nl/92236/]

De Wit, R. (2011). Biodiversity of Coastal Lagoon Ecosystems and their Vulnerability to Global Change. In: Grillo, O. & Venora, G. (Eds.), *Ecosystems Biodiversity*., InTech, Rijeka, Croatia: 29-40.

Debrot, A.O., Hylkema, A., Vogelaar, W., Prud'homme van Reine, W.F., Engel, M.S., van Hateren, J.A., & Meesters, E.H. (2019). Patterns of distribution and drivers of change in shallow seagrass and algal assemblages of a non-estuarine Southern Caribbean mangrove lagoon. *Aquatic Botany, 159*, 103148. https://doi.org/10.1016/j.aquabot.2019.103148

Dekker, A., Vos, R.J., & Peters, W.M. (2002). Analytical algorithms for lake water TSM estimation for retrospective analyses of TM and SPOT sensor data. *International Journal of Remote Sensing*, *23*(1), 15-35.

Dobbs, K., Day, J., Skeat, H., Baldwin, J., Molloy, F., McCook, F., Johnson, M., Elliot, B., Skeat, A., Vohland, K., Wachenfeld, D., & Kenchington, R. (2011). Developing a long term outlook for the Great

Barrier Reef, Australia: a framework for adaptive management reporting underpinning an ecosystem-based management approach. *Marine Policy*, *35*, 233-240.

Elliot, M., & Quintino, V. (2007). The Estuarine Quality Paradox, Environmental Homeostasis and the difficulty of detecting anthropogenic stress in naturally stressed areas. *Mar. Pollut. Bull.*, *54*(6), 640-645.

Esteves, F.A., Caliman, A., Santangelo, J.M., Guariento, R.D., Farjalla, V.F., & Bozelli, R.L. (2008). Neotropical coastal lagoons: An appraisal of their biodiversity, functioning, threats and conservation management. *Brazilian Journal of Biology, 68*, 631-637.

EU (2000). Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities* L 327.

European Commission (2015). *Investing in European success. A decade of success in Earth Observation Research and Innovation.* 52 pp.

Evans, G. (2008). Man's Impact on the Coastline. *Journal of Iberian Geology, 34*(2), 167-190.

Finkl, C.W., & Makowski, C. (Eds.) (2014). *Remote Sensing and Modeling, Advances in Coastal and Marine Resources*. Coastal Research Library, 9, Springer International Publishing.

Fitoka, E., & Keramitsoglou, I. (Eds.) (2008). *Inventory, assessment and monitoring of Mediterranean Wetlands: Mapping wetlands using Earth Observation techniques.* EKBY & NOA MedWet publication.

Gaertner-Mazouni, N., & De Wit, R. (2012). Exploring new issues for coastal lagoons monitoring and management. *Estuarine, Coastal and Shelf Science*, *114*, 1-6.

Gervan, C., & Marshall, M.L. (1977). *Landsat investigation of water quality in Lake Okeechobee.* ASP-ACSM Conference (Washington, DC).

Gordon, H.R., & Morel, A.Y. (1983). *Remote assessment of ocean color for interpretation of satellite visible imagery. A review of lecture notes on coastal and estuarine studies.* New York: Springer-Verlag.

Han, S., Li, C., Li, M., Lenzen, M., Chen, X., Zhang, Y., Li, M., Yin, T., Li, Y., Li, J., Liu, J., & Li, Y. (2024). Prospects for global sustainable development through integrating the environmental impacts of economic activities. *Nat. Commun.*, *15*, 8424. https://doi.org/10.1038/s41467-024-52854-w

Haines, P.E., Tomlinson, R.B., & Thom, B.G. (2006). Morphometric assessment of intermittently open/closed coastal lagoons in New South Wales, Australia. *Estuarine, Coastal and Shelf Science 67*(1-2), 321-332. https://doi.org/10.1016/j.ecss.2005.12.001

Hayes, M.O. (1979). Barrier island morphology as a function of tidal and wave regime. In: Leatherman S.P. (Ed.), *Barrier Islands.* New York: Academic Press, pp. 1-27.

Hedley, J.D., Roelfsema, C., Brando, V., Giardino, C., Kutser, T., Phinn, S., Mumby, P.J., Barrilero, O., Laporte, J., & Koetz, B. (2018). Coral reef applications of Sentinel-2: Coverage, characteristics, bathymetry and benthic mapping with comparison to Landsat 8. *Remote Sensing of Environment*, *216*, 598-614.

IMDC (2025). Internal Displacement Monitoring Centre. [Accessed online June 2025: https://www.internal-displacement.org/countries/bangladesh/]

IOCCG (2000). Remote Sensing of Ocean Colour. In: Sathyendranath, S. (Ed.), *Coastal, and Other Optically-Complex Waters,* Reports of the International Ocean Colour Coordinating Group. Dartmouth, Canada.

IOCCG (2018). Earth Observation. In: Greb. S., Dekker, A. & Binding, C. (Eds.). *Support of Global water quality monitoring.* IOCCG Report Series, 17, International Ocean Colour Coordinating Group, Dartmouth, Canada.

IUCN (2020). *Guidance for Using the IUCN Global Standard for Nature-Based Solutions: a User-Friendly Framework for the Verification, Design and Scaling* Up of Nature Based Solutions. IUCN, Gland, Switzerland. https://doi.org/10.2305/IUCN.CH.2020.09.en

Joyeux, J.C., & Ward, aAB. (1998) Constraints on Coastal Lagoon Fisheries. *Advances in Marine Biology, 34*, 73-199. https://doi.org/10.1016/S0065-2881(08)60211-4

Kachelriess, D., Wegmann, M., Gollock, M.,& Pettorelli, N. (2014). The application of remote sensing for marine protected area management. *Ecological Indicators, 36*, 169-177.

Kennish, M.J. (2015). Coastal Lagoons. In: Kennish, M.J. (Ed.), Encyclopedia of Estuaries. Springer, pp. 140-143.

Kennish, M.J., & de Jonge V.N. (2011). Chemical introductions to the systems: diffuse and nonpoint source pollution from chemicals (nutrients: eutrophication). In: Kennish, M.J. & M. Elliott, M. (Eds.), Treatise on estuarine and coastal science, vol. 8, human-induced problems (uses and abuses). London: Elsevier, pp. 113-148.

Kjerfve, B. (1994). Coastal Lagoons. In: Kjerfve, B. (Ed.), *Coastal Lagoon Processes.* Elsevier Oceanography Series: 1-8. doi: doi:10.1201/EBK1420088304-c1

Kong, Y., Jimenez, K., Lee, C. M., Winter, S., Summers-Evans, J., Cao, A., Menczer, M., Han, R., Mills, C., McCarthy, S., Blatzheim, K., & Jay, J. A. (2025). Monitoring Coastal Water Turbidity Using Sentinel2 - A Case Study in Los Angeles. *Remote Sensing*, *17*(2), 201. https://doi.org/10.3390/rs17020201

Kutser, T. (2012). The possibility of using the Landsat image archive for monitoring long time trends in coloured dissolved organic matter concentration in lakes. *Remote Sensing of Environment, 123*, 334-338.

Kutser, T., Hedley, J., Giardino, C., Roelfsema, C., & Brando, V.E. (2020). Remote sensing of shallow Waters- 50 year retrospective and future directions. *Remote Sensing of Environment*, *240,* 111619.

Lester, S.E., McLeod, K.L., Tallis, H., Ruckelshaus, M., Halpern, B.S., Levin, P.S., Chavez, F.P., Pomeroy, C., Mc Cay, B.J., Costello, C., Gaines, S.D., Mace, A.J., Barth, J.A., Fluharty, D.L., & Parrish, J.K. (2010). Science in support of ecosystem based management for the US west coast and beyond. *Biological Conservation, 143,* 576-587.

Luis, K.M.A., Rhuban, J.E., Kavanaugh, M.T., Glover, D.M., Wei, J., Lee, Z., & Doney, S.C. (2019). Capturing coastal water clarity variability with Landsat 8. *Marine Pollution Bulletin, 145*, 96-104. https://doi.org/10.1016/j.marpolbul.2019.04.078.

Mahapatro, D., Panigraphy, R.C., & Panda, S. (2013). Coastal lagoon: Present status and future challenges. *International Journal of Marine Science, 3*(23), 178-186.

Mazzilli, S., & Christian, R. (2007). Defining the coast and sentinel ecosystems for coastal observations of global change. *Hydrobiologia, 577*, 55-70.

Meng, H., Zhang, J., Zheng, Z., Song, Y., & Lai, Y. (2024). Classification of inland lake water quality levels based on Sentinel-2 images using convolutional neural networks and spatiotemporal variation and driving factors of algal bloom. *Ecological Informatics, 80*, 102549. https://doi.org/10.1016/j.ecoinf.2024.102549

Miller, R.L., Del Castillo, C.E., & Mckee, B.A. (2005). *Remote sensing of coastal aquatic environments: Technologies, techniques, and applications.* Springer.

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.

Nayak, P.K., & Berkes, F. (2014). Linking global drivers with local and regional change: a social-ecological system approach in Chilika lagoon, Bay of Bengal. *Regional Environmental Change, 14*(6), 2067-2078. https://doi.org/10.1007/s10113-012-0369-3

Nayak P.K., Armitage, D., & Andrachuk, M. (2016). Power and politics of social-ecological regime shifts in the Chilika lagoon, India and Tam Giang lagoon, Vietnam. *Regional Environmental Change, 16*, 325-339.

Neumann, B., Vafeidis, A.T., Zimmermann, J., & Nicholls, R.J. (2015). Future coastal population growth and exposure to sea level rise and coastal flooding – a global assessment. *PLoS ONE, 10*(3) e0118571. https://doi.org/10.1371/journal.pone.0118571

Newton, A., Icely, J., Cristina, S.n., Brito, A., Cardoso, A.C., Colijn, F., Riva, S.D., Gertz, F., Hansen, J.W.r., Holmer, M., et al. (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*(Supplement C), 95-122.

Newton, A.C. Brito, J.D. Icely, V. Derolez, I. Clara, S. Angus, G. Schernewski, M. Inácio, A.I. Lillebø, A.I. Sousa, B. Béjaoui, C. Solidoro, M. Tosic, M. Cañedo-Argüelles, M. Yamamuro, S. Reizopoulou, et al. (2018). Assessing, quantifying and valuing the ecosystem services of coastal lagoons. *Journal for Nature Conservation, 44*, 50-65. https://doi.org/10.1016/j.jnc.2018.02.009

Niroumand-Jadidi, M., Bovolo, F., Bresciani, M., Gege, P., & Giardino, C. (2022). Water Quality Retrieval from Landsat-9 (OLI-2) Imagery and Comparison to Sentinel-2. *Remote Sensing*, *14*(18), 4596. https://doi.org/10.3390/rs14184596

Nixon, S.W. (1995). Coastal eutrophication: A definition, social causes, and future concerns. *Ophelia*, *41*, 199-220.

O'Leary, B., Wood, L.E., Cornet, C., Roberts, C., & Fonseca, C. (2024). Practitioner insights on challenges and options for advancing blue Nature-based Solutions. *Marine Policy, 163*, 106104. https://doi.org/10.1016/j.marpol.2024.106104

O'Leary, B.C., Fonseca, C., Cornet, C.C., de Vries, M.B., Degia, A.K., Failler, P., Furlan, E., Garrabou, J., Gil, A., Hawkins, J.P., Krause-Jensen, D., Le Roux, X., Peck, M.A., Pérez, G., et al. (2023). Embracing Nature-based Solutions to promote resilient marine and coastal ecosystems. *Nature-Based Solutions, 3*, 100044.

Palmer, S., Kutser, T., & Hunter, P. (2015). Remote sensing of inland waters: Challenges, progress and future directions. *Remote Sens. Environ.*, *157*, 1-8.

Pérez, G., O'Leary, B., Allegri, E., Casal, G., Cornet, C.C., de Juan, S., Failler, P., Fredriksen, S., Fonseca, C., Furlan, E., Gil, A., Hawkins, J.P., Mérechal, J.P., McCarthy, T., Roberts, C.M., Trégarot, E., van der Geest, M., & Simide, R. (2024). A conceptual framework to help choose appropriate blue nature-based solutions. *Journal of Environmental Management, 352*, 119936. https://doi.org/10.1016/j.jenvman.2023.119936

Pérez-Ruzafa, A., & Marcos, C. (2008). Coastal lagoons in the context of water management in Spain and Europe. In: Gönenç, İ.E., Vadineanu, A., Wolflin, J.P. &, Russo, R.C. (Eeds.), *Sustainable Use and Development of Watersheds*. Netherlands: Springer, pp. 299-321.

Pérez-Ruzafa, A., & Marcos, C. (2012). Fisheries in coastal lagoons: an assumed but poorly researched aspect of the ecology and functioning of coastal lagoons. *Estuar. Coast. Shelf Sci., 110*, 15-31.

Pérez-Ruzafa, A., & Marcos, C. (2015). Monitoring heterogeneous and quick-changing environments: coping with spatial and temporal scales of variability in coastal lagoons and transitional waters. In: Sebastiá, M. (Ed.), *Coastal Ecosystems: Experiences and Recommendations for Environmental Monitoring.* New York: Nova Science Publishers, pp. 89-116.

Pérez-Ruzafa, A., Mompeán, M.C., & Marcos, C. (2007). Hydrographic, geomorphologic and fish assemblage relationships in coastal lagoons. *Hydrobiologia, 577*, 107-125.

Pérez-Ruzafa, A., Marcos, C. & Pérez-Ruzafa, I.M. (2011a). Recent advances in coastal lagoons ecology: evolving old ideas and assumptions. *Transitional Waters Bulletin*, *5*(1), 50-74. https://doi.org/10.1285/i1825229Xv5n1p50

Pérez-Ruzafa, A., Marcos, C., Pérez-Ruzafa, I.M., & Pérez-Marcos, M. (2011b). Coastal lagoons: "transitional ecosystems" between transitional and coastal waters. *Journal for Coastal Conservation, 15*(3), 369-392. https://doi.org/10.1007/s11852-010-0095-2

Pérez-Ruzafa, A., Pérez-Ruzafa, I.M., Newton, A., & Marcos, C. (2019). Coastal Lagoons: Environmental Variability, Ecosystem Complexity, and Goods and Services Uniformity. In: Wolanski, E., Day, J., Elliott, M. & Ramesh, R. (Eds), *Coasts and Estuaries: The Future.* Elsevier, pp. 253-276. https://doi.org/10.1016/B978-0-12-814003-1.00015-0

Pérez-Ruzafa, A., Molina-Cuberos, G. J., García-Oliva, M., Umgiesser, G., & Marcos, C. (2024). Why are coastal lagoons so productive? Physical bases of fishing productivity in coastal lagoons. *Science of The Total Environment*, *922*, 171264. https://doi.org/10.1016/j.scitotenv.2024.171264

Pitacco, V., Mistri, M., & Munari, C. (2018). Long-term variability of macrobenthic community in a shallow coastal lagoon (Valli di Comacchio, northern Adriatic): is community resistant to climate changes? *Mar. Environ. Res., 137*, 73-87.

Ramesh, R., Chen, Z., Cummins, V., Day, J., D'Elia, C., Dennison, B., Forbes, D.L., Glaeser, B., Glaser, M., Glavovic, B., Kremer, H., Lange, M., Larsen, J.N., Le Tissier, M., Newton, A., Pelling, M., Purvaja, R., & Wolanski, E. (2015). Land–Ocean Interactions in the Coastal Zone: Past, present & future. *Anthropocene, 12*, 85-98. https://doi.org/10.1016/j.ancene.2016.01.005

Reid, W.V., Chen, D., Goldfarb, L., Hackmann, H., Lee, Y.T., Mokhele, K., Ostrom, E., Raivio, K., Rockstrom, J., Schellnhuber, H.J., & Whyte, A. (2010). Earth System Science for Global Sustainability: Grand Challenges. *Science, 330*(6006), 916-917.

Reimann, L., Vafeidis, A.T., & Honsel, L.E. (2023). Population development as a driver of coastal risk: Current trends and future pathways. *Cambridge Prisms: Coastal Futures*, *1*(e14), 1-12. https://doi.org/10.1017/cft.2023.3

Rodrigues-Filho, J.L., Macêdo, R.L., Sarmento, H., Pimenta V.R.A., Alonso, C., Teixeira, C.R., Pagliosa, P.R., Netto, S.A., Santos, N.C.L., Daura-Jorge, F.G., Rocha, O., Horta, P., Branco, J.O., Sartor, R., Muller, J., & Cionek, V.M. (2023). From ecological functions to ecosystem services: linking coastal lagoons biodiversity with human well-being. *Hydrobiologia, 850*, 2611-2653.

Rotta, L., Alcantara, H., Watanabe, F. Rodrigues, T., & Imai, N.N. (2016). Atmospheric correction assessment of SPOT-6 image and its influence on models to estimate water column transparency in tropical reservoirs. *Remote Sensing Applications: Society and Environment*, *4*, 158-166.

Salls, W. B., Schaeffer, B. A., Pahlevan, N., Coffer, M. M., Seegers, B. N., Werdell, P. J., Ferriby, H., Stumpf, R. P., Binding, C. E., & Keith, D. J. (2024). Expanding the Application of Sentinel-2 Chlorophyll Monitoring across United States Lakes. *Remote Sensing*, *16*(11), 1977. https://doi.org/10.3390/rs16111977

Seixas, C.S. (2002). *Social ecological dynamics in management systems: Investigating a coastal lagoon fishery in Southern Brazil*. PhD thesis, University of Manitoba, Winnipeg, Canada.

Selig, U., Eggert, A., Schories, D., Schubert, M., Blumel, C., & Schubert, H. (2007). Ecological classification of macroalgae and angiosperm communities of inner coastal waters in the southern Baltic sea. *Ecological Indicators*, *7*, 665-678.

Soria, J., Pérez, R., & Sòria-Pepinyà, X. (2022). Mediterranean Coastal Lagoons Review: Sites to Visit before Disappearance. *J. Mar. Sci. Eng. 10*, 347. https://doi.org/10.3390/jmse10030347

Suusaar, Ü., Torn, K., Mäemets, H., & Rosantau, A. (2024). Overview and evolutionary path of Estonian coastal lagoons. *Estuarine, Coastal and Shelf Science*, *303*, 108811.

Tagliapietra, D., Sigovini, M., & Volpi-Ghirardini, A.V. (2009). A review of terms and definitions to categorise estuaries, lagoons and associated environments. *Marine and Freshwater Research, 60*(6), 497-509.

Tagliapietra, D., Aloui-Bejaoui, N., Bellafiore, D., De Wit, R., Ferrarin, C., Gamito, S., Lasserre, P., Magni, P., Mistri, M., Pérez-Ruzafa, A., Pranovi, F., Reizopoulou, S., Rilov, G., Solidoro, C., Tunberg, B., Valiela, I., & Viaroli, P. (2011). *The Ecological Implications of Climate Change on the Lagoon of Venice.* Report for the Workshop organised by UNESCO Venice Office and ISMAR-CNR, 26-27 May 2011, Italy.

Toming, K., Kutser, T., Lass, A., Sepp, M., Paavel, B., & Noges, T. (2016). First experiences in mapping lake water quality parameters with Sentinel-2 MSI imagery. *Remote Sensing*, *8*(8), 640.

Turner II, B.L., Matson, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Hovelsrud-Broda, G.K., Kasperson, J.X., Kasperson, R.E., Luers, A., Martello, M.L., Mathiesen, S., Naylor, R., Polsky, C., Pulsipher, A., Schiller, A., Selin, H., & Tyler, N. (2003). Illustrating the coupled human-environment systems for vulnerability analysis: three case studies. *Proceedings of the National Academy of Sciences, 100*(14), 8080-8085. http://dx.doi.org/10.1073/pnas.1231334100

Tyler, A.N., Hunter, P., Spyrakos, E., Groom, S., Constantinescu, A.C., & Kitchen, J. (2016). Developments in Earth Observation for the assessment and monitoring of inland, transitional, coastal and shelf-sea waters. *Science of the Total Environment, 572*, 1307-1321.

United Nations (2010). *World population prospects: The 2010 revision - highlights and advance tables*. Working Paper No ESA/P/WP220. Department of Economic and Social Affairs, Population Division, New York.

Valiela, I. (1995). *Marine Ecological Processes*- SpringerVerlag, New York.

Volpe, G., Colella, S., Forneris, V., Tronconi, C., & Santoleri, R. (2012). The Mediterranean Ocean Colour Observing System – system development and product validation. *Ocean Sci.*, *8*, 869-883.

Werdell, P.J., Behrenfeld, M.J., Bontempi, P.S., Boss, E., Cairns, B., Davis, G.T., Franz, B.A., Gliese, U.B., Gorman, E.T., Hasekamp, O., Knobelspiesse, K.D., Mannino, A., Martins, J.V., McClain, C.R., Meister, G., & Remer, L.A. (2019). The plankton, aerosol, cloud, ocean ecosystem (PACE) mission: Status, science, advances. *Bull. American Meteorological Society, 100*(9), 1775-1794. https://doi.org/10.1175/BAMS-D-18-0056.1

Whitfield, A.K. (2011). Coastal Lagoons – Critical Habitats of Environmental Change, *Marine Biology Research*. https://doi.org/10.1080/17451000.2010.538064

World Water Quality Alliance (2021). *World Water Quality Assessment: First Global Display of a Water Quality Baseline. A consortium effort by the World Water Quality Alliance - towards a full global assessment.* Information Document Annex for display at the 5th Session of the United Nations Environment Assembly (UNEA-5), Nairobi 2021.

APPENDIX

List of goals, priorities, and targets stemming from global aspirations and agreements that are relevant to coastal lagoons

Initiative	Brief description	Action
UN Sustainable Development Goals	The United Nations (UN) conference on Sustainable Development led to the development of the 2030 Agenda, which consists of 17 Sustainable Development Goals (SDGs). The 2030 Agenda for Sustainable Development was agreed and adopted by the UN General Assembly, and each member government is required to take action to promote prosperity while protecting the environment. The SDGs consist of 169 targets and are supported by 247 indicators, which are intended as management tools for each country to implement sustainable development strategies and support the reporting of progress towards SDG targets. Conducting environmental management inventories of coastal lagoons requires taking into consideration SDGs as directive policies for monitoring and reporting obligations, and which involves holistic analysis of different data sources such as EO.	Goal 6. Ensure availability and sustainable management of water and sanitation for all.
		Target 6.3: By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.
		Target 6.5: By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate.
		Target 6.6: By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes.
		Target 6.a: By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies.
		Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable.
		Target 11.6: By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.

Initiative	Brief description	Action
		Target 11.b: By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015-2030, holistic disaster risk management at all levels.
		Goal 12. Ensure sustainable consumption and production patterns.
		Target 12.2: By 2030, achieve the sustainable management and efficient use of natural resources.
		Goal 13. Take urgent action to combat climate change and its impacts.
		Target 13.1: Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries.
		Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development.
		Target 14.1: By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution.
		Target 14.2: By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans.
		Target 14.3: Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels.

Initiative	Brief description	Action
		Target 14.4: By 2020, effectively regulate harvesting and end overfishing, illegal, unreported and unregulated fishing and destructive fishing practices and implement science-based management plans, in order to restore fish stocks in the shortest time feasible, at least to levels that can produce maximum sustainable yield as determined by their biological characteristics.
		Target 14.5: By 2020, conserve at least 10 per cent of coastal and marine areas, consistent with national and international law and based on the best available scientific information.
		Target 14.7: By 2030, increase the economic benefits to small island developing States and least developed countries from the sustainable use of marine resources, including through sustainable management of fisheries, aquaculture and tourism.
		Target 14.b: Provide access for small-scale artisanal fishers to marine resources and markets.
		Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.
		Target 15.5: Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species.
		Target 15.7: Take urgent action to end poaching and trafficking of protected species of flora and fauna and address both demand and supply of illegal wildlife products.
		Target 15.8: By 2020, introduce measures to prevent the introduction and significantly reduce the impact of invasive

Initiative	Brief description	Action
		alien species on land and water ecosystems and control or eradicate the priority species.
		Target 15.9: By 2020, integrate ecosystem and biodiversity values into national and local planning, development processes, poverty reduction strategies and accounts.
		Target 15.a: Mobilize and significantly increase financial resources from all sources to conserve and sustainably use biodiversity and ecosystems.
		Target 15.c: Enhance global support for efforts to combat poaching and trafficking of protected species, including by increasing the capacity of local communities to pursue sustainable livelihood opportunities.
COP21 and Paris Agreement	The COP21 Paris Agreement provided guidelines to strengthen global responses as measures to climate change threat and reducing carbon emissions in a context of sustainable development. Coastal lagoons could play a major role in achieving the agreement objectives because they are considered important Blue Carbon sinks[1,2]. The COP events expect countries to come forward with ambitious 2030 emissions reductions targets to reach net zero emission by 2050, and to adapt to protect communities and natural habitats. Therefore, raising awareness regarding the importance of coastal lagoons as hotspot ecosystems	

[1] Sousa, A.I., da Silva, J.F., Azevedo, A. *et al.* (2019). Blue Carbon stock in *Zostera noltei* meadows at Ria de Aveiro coastal lagoon (Portugal) over a decade. *Sci Rep, 9*, 14387. https://doi.org/10.1038/s41598-019-50425-4

[2] Brevik, E.C., & Homburg, J.A. (2004). A 5000 year record of carbon sequestration from a coastal lagoon and wetland complex, Southern California, USA. *Catena, 57*(3), 221-232. https://doi.org/10.1016/j.catena.2003.12.001

Initiative	Brief description	Action
	for Blue Carbon could provide an importance source of knowledge into achieving the goals.	
Strategic Plan for Biodiversity 2011–2020 and the Aichi Targets	2011-2020 was the UN decade on Biodiversity following global recognition of the urgent need for action against continuing biodiversity loss. The Strategic Plan for Biodiversity 2011-2020 served as a framework to promote implementation of the three objectives of the Convention on Biological Diversity (CBD), which was signed and entered into force in 1993. Under the Strategic Plan for Biodiversity, the Aichi Targets include five strategic goals, all relevant and applicable to coastal lagoon social-ecological systems.	Strategic Goal A: Address the underlying causes of biodiversity loss by mainstreaming biodiversity across government and society.
		Strategic Goal B: *Reduce the direct pressures on biodiversity and promote sustainable use*.
		Strategic Goal C: To improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity.
		Strategic Goal D: Enhance the benefits to all from biodiversity and ecosystem services.
		Strategic Goal E: Enhance implementation through participatory planning, knowledge management and capacity building.
Sendai Framework for Disaster Risk Reduction (DRR	The Sendai Framework for Disaster Risk Reduction (DRR) considers three dimensions of disaster risk: namely exposure to hazards, vulnerability and capacity, and the characteristics of the hazard. By adopting suitable measures to address all three dimensions, nations can reduce existing risks, prevent the creation of new risks and increase resilience. The Sendai Framework has outlined four priorities for action and seven global targets.	Priority 1: Understand disaster risk.
		Priority 2: Strengthen disaster risk governance to manage disaster risk.
		Priority 3: Invest in DRR for resilience.
		Priority 4: Enhance disaster preparedness for effective response, and “build back batter” in recovery, rehabilitation and reconstruction.