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Présentée et soutenue le 19/09/2020 par :

Badr EL MAHRAD

Contribution of Remote Sensing to a Holistic Coastal and Marine Environmental Management Framework: An integrated Pan-African Perspective on North Africa Coastal Lagoons Management

JURY

Saida NIAZI	PES, Faculté des Sciences, Université Mohammed V, Rabat	Présidente
Ilias KACIMI	PES, Faculté des Sciences, Université Mohammed V, Rabat	Directeur de Thèse
Alice NEWTON	PES, Centre de Recherche Marine et Environnemental Université d'Algarve, Faro, Portugal	Rapporteur/Examineur
Nadia KASSOU	PES, Faculté des Sciences, Université Mohammed V, Rabat	Rapporteur/Examineur
Mohammed ACHAB	PES, Institut Scientifique, Université Mohammed V, Rabat	Rapporteur/Examineur
Moad MORARECH	PES, Faculté des Sciences, Université Abdelmalek Essaâdi, Tétouane	Examineur
Abdessamad EL ADRAOUI	PES, Faculté des Sciences, Université Mohammed V, Rabat	Examineur
John David ICELY	HDR, Centre de Recherche Marine et Université d'Algarve, Faro, Portugal	Examineur
Karim HILMI	HDR, Directeur de Recherche, Institut National de Halieutique, Casablanca	Invité
Maria SNOUSSI	PES, Présidente du Conseil Scientifique, Institut de Recherche pour le Développement – France	Invitée

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Avant-Propos

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² 4th edition of the Mediterranean Conservation Science Conference et Eurolag 2020.

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RÉSUMÉ

Tous les environnements côtiers et marins sont au centre des enjeux socio-économiques, particulièrement les lagunes côtières. Elles figurent parmi les écosystèmes les plus productifs au monde. Parmi elles, les lagunes côtières d'Afrique du Nord qui fournissent des services écosystémiques précieux pour le bien-être de la population. Néanmoins, l'évaluation des menaces environnementales, révèle souvent le manque de données actualisées. Le thème de la présente recherche est d'appliquer un cadre fédérateur en utilisant les données de la télédétection pour pallier aux lacunes et faciliter une gestion intégrée de ces milieux. L'approche intégrée DAPSI(W)R(M) est appliquée sur onze lagunes côtières en Afrique du Nord. En outre, une contribution des technologies de télédétection au même cadre de la gestion est présentée pour aider les pays concernés à mettre en œuvre leurs directives environnementales. Finalement, l'exemple de la contribution de la télédétection pour combler des lacunes dans la mise en œuvre du cadre DAPSI(W)R(M) est appliquée à la lagune de Nador (Maroc). Les informations obtenues sur certaines activités, pressions, changements d'état, permettent d'y détecter les diverses menaces. Quelques options de mesures de gestion sont proposées. Toutefois, un suivi des lagunes à l'aide des technologies de la télédétection permettrait d'obtenir une meilleure analyse par DAPSI(W)R(M) pour une gestion holistique et un développement durable des lagunes côtières.

Mots-clefs : Lagunes côtières, Afrique du Nord, cadre DAPSI(W)R(M)- Télédétection, Gestion holistique –Développement durable- Lagune Nador (Maroc).

ABSTRACT

Coastal and marine environments are at the centre of socio-economic concerns, particularly coastal lagoons. They are among the most productive ecosystems in the world, such as the case of North African lagoons, which provide valuable ecosystem services for the human welfare. However, assessing environmental threats often reveals a lack of up-to-date data. The aim of this research is to apply a holistic framework using remote sensing data to overcome the gaps and facilitate an integrated management of these environments. The integrated DAPSI(W)R(M) approach is applied to eleven North African coastal lagoons. In addition, a contribution of remote sensing technologies to the same management framework is presented, which will support the concerned countries to implement their environmental directives. Finally, an example of remote sensing contribution to fill gaps in the implementation of the DAPSI(W)R(M) framework is applied to the Nador lagoon (Morocco). The obtained information on certain activities, pressures, state changes, makes it possible to detect various threats. Management options (as measures) are proposed. Therefore, lagoons monitoring using remote sensing technologies would allow a better analysis using DAPSI(W)R(M) for a holistic management and a sustainable development of coastal lagoons.

Key Words: Coastal Lagoons, North Africa, DAPSI(W)R(M) Framework, Holistic Management, Sustainable Development, Nador Lagoon (Morocco)

RÉSUMÉ DÉTAILLÉ

Ce sujet recherche donne un aperçu des environnements côtiers et marins, y compris des lagunes côtières d'Afrique du Nord. Ces environnements complexes sont essentiels et fournissent des services écosystémiques précieux pour le bien-être de leur population. Cependant, lorsqu'on évalue les multiples menaces environnementales des pays d'Afrique du Nord, comme de nombreuses régions du monde, il est constaté le peu d'accès, ou l'absence totale d'accès à des données essentielles.

Dans ce sens, la télédétection peut contribuer à combler ces lacunes afin que les pays et les agences environnementales, telles que le Programme des Nations Unies pour l'Environnement, l'Agence Européenne pour l'Environnement et l'Union Internationale pour la Conservation de la Nature, puissent mieux appliquer les directives environnementales de manière rentable.

Cette recherche a suivi l'approche DAPSI(W)R(M) framework ; Drivers-Activities-Pressures-State Change- Impact (on Welfare)-Responses (as Measures); afin d'analyser les conditions environnementales, les vulnérabilités et les perspectives futures qui aideront les décideurs à fournir des solutions pour le développement durable. En outre, les résultats montrent que cette approche est un outil précieux et important, non seulement pour fournir des informations aux gestionnaires de l'environnement, mais également pour fournir des indications pratiques pour la gestion intégrée de ces écosystèmes et démontrer l'utilité des technologies de télédétection pour soutenir la mise en œuvre des objectifs, descripteurs, cibles et politiques environnementaux, tels que la directive-cadre sur l'eau, la directive-cadre "Stratégie pour le milieu marin", l'indice de santé des océans et les objectifs de développement durable des Nations unies

Finalement, l'exemple de la contribution de la télédétection pour combler des lacunes dans la mise en œuvre du cadre DAPSI(W)R(M) est appliquée à la lagune de Nador (Maroc).

La présente thèse est structurée en trois (3) parties.

La première partie (1) est consacrée à l'état des lieux des environnements côtiers et marins et notamment des lagunes avec leurs différentes typologies, afin de présenter une analyse critique des lagunes côtières et des projets antérieurs portant sur ces écosystèmes en Afrique du Nord.

La deuxième partie (2) donne un aperçu des lagunes choisies et de leurs caractéristiques générales. Elle examine le cadre de gestion environnementale holistique et intégrée existant en

tant que méthodes pouvant être utilisées pour la gestion des différentes zones côtières et marines, y compris les lagunes. Cette partie s'est concentrée en profondeur sur la méthodologie employée dans cette thèse, qui est le cadre DAPSI(W)R(M), afin d'analyser, d'évaluer et d'aider à fournir des options de gestion aux gestionnaires, aux décideurs politiques et aux scientifiques. En outre, les technologies de télédétection appliquées à la gestion des côtes et du milieu marin ont été présentées.

La troisième partie (3) est consacrée à l'analyse des résultats et à la discussion. Le premier chapitre présente une analyse socio-environnementale pour la gestion de 11 lagunes côtières en Afrique du Nord en utilisant le DAPSI(W)R(M) comme cadre de gestion environnementale intégrée holistique.. Le deuxième chapitre montre la contribution des technologies de télédétection au même cadre de gestion qui aidera de nombreux pays à mettre en œuvre leurs directives environnementales pour leurs zones côtières et marines, y compris les lagunes. Par exemple, la directive-cadre sur l'eau, la directive-cadre "Stratégie pour le milieu marin", l'objectif de développement durable et l'indice de santé des océans. Le troisième chapitre présente un exemple d'utilisation des technologies de télédétection pour combler les lacunes dans la mise en œuvre du cadre DAPSI(W)R(M).

Finalement, après la conclusion générale, les perspectives d'avenir, les recommandations ainsi que les références citées sont énumérées.

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ACRONYMS

ARS: Aerial Remote Sensing

BQE: Biological Quality Elements

EU: European Union

EVI : Enhanced vegetation index

HAB: Harmful Algal Blooms

HQE: Hydromorphological Quality Elements

IUCN: International Union for Conservation of Nature

MSFD: Marine Strategy Framework Directive

NDWI: Normalized difference water index

OHI: Ocean Health Index

P-CQE: Physico-Chemical Quality Elements

SAF: System Approach Framework

SDG: Sustainable Development Goals

SES: Social-Ecological Systems

SMOS: Soil Moisture and Ocean Salinity

SRS: Satellite Remote Sensing

SS: Static Sensors

SSS: Sea Surface Salinity

UAV: Unmanned Aerial Vehicles

UN: United Nations

UNEP: United Nations for Environmental Protection

USV: Unmanned Surface Vehicles

UUV: Unmanned Underwater Vehicles

WFD: Water Framework Directive

GENERAL INTRODUCTION

Coastal and marine areas, including lagoons, are among the most productive environments and deliver ecosystem services, that provide many ecological, cultural and socio-economic benefits supporting a range of natural services that are highly valued by society (Gönenç and Wolflin, 2005). These include food with fisheries productivity, transport, renewable energies, natural resources, nutrient cycling, water purification, climate and water regulation, as well as creating recreational values from storms, aesthetic and inspirational values and also tourism.

Therefore, the management of these ecosystems require the evaluation of multiple environmental threats and issues and solving conflicts among different stakeholders (extractors inputters, beneficiaries, affectees, regulators, influencers) (Newton and Elliott, 2016).

For instance, North African coastal and marine environments, and especially costal lagoons provide many important economic resources, from fishing activities (fish and shellfish) to tourism. Many of them are classified as RAMSAR sites and contribute substantially to regional biodiversity but many human activities and intervention alter the functioning of lagoon systems and affect the health of lagoon ecosystems. Many studies, reports and research projects that have been done in North African lagoons define physical characteristics, biological diversity, ecological states, geochemical contamination, hydrological and dynamic modification. However, none of these studies considered into details the management aspect from both environmental and social aspects.

The first objective of this research is to provide an analysis of the current state of north African lagoons using the integrated management framework, DAPSI(W)R(M) *Drivers – Activities – Pressures - Impacts (on Welfare) - Responses (as Measures)*. It is known before as DPSIR; framework to analyse human drivers, pressures, ecological state and the impact on human welfare, and then on to societal responses which will need to provide management solutions based on scientific knowledge (Gari *et al.*, 2015; Patrício *et al.*, 2016; Elliott *et al.*, 2017a). Therefore, the scientific knowledge base for the appropriate management of coastal lagoons as socio-ecological systems in North Africa, could help to bring sustainable management for the future.

The knowledge gaps found in North African studies, which is due mainly to the lack of data or poor dissemination or communication, has led to assess in depth the possible cost-effective technologies that can help assessing coastal and marine environment not only in north African countries but to solve this issue on a large scale, worldwide.

The second objective of this research is to assess and show the contribution of remote sensing to a holistic coastal and marine environmental framework which will help later to: (1) achieve equilibrium between ecological, social and economic sectors of the coastal and marine system and (2) to explore their dynamics, as well as, the possible consequences of alternative policy scenarios.

Achieving both objectives requires a reorganization of the science-based knowledge to comprehend the interactions between multifaceted natural and social systems at different spatial and temporal scales including the overall economic evaluation of alternative policies.

The thesis is structured in three (3) parts.

The first part (1) is dedicated to the state-of-the-art about coastal and marine environments and especially lagoons with their different typologies, to present a critical analysis about coastal lagoons and previous projects dealing with these ecosystems in North Africa.

The second part (2) gives an overview of the chosen lagoons and their general characteristics. It discusses the existing holistic and integrated environmental management framework as methods that could be used for the management of the different coastal and marine areas, including lagoons. This part focused in depth on the methodology employed in this thesis, which is the DAPSI(W)R(M) framework, in order to analyse, assess and help to provide management options to managers, policy makers and scientist. Furthermore, remote sensing technologies applied to coastal and marine management were presented.

The third part (3) is dedicated to the analysis of the results and to the discussion. The first chapter present a social-environmental analysis for the management of 11 coastal lagoons in north Africa using the DAPSI(W)R(M) as a holistic integrated environmental management framework. presented the results of the study. The second chapter shows the contribution of remote sensing technologies to the same management framework which will help many countries on implementing their environmental directives for their coastal and marine areas, including lagoons such us the Water Framework Directive, the Marine Strategy Framework Directive, the Sustainable Development Goal and the Ocean Health Index. The third chapter present an example of using remote sensing technologies to fill the gap in the implementation of the DAPSI(W)R(M) framework applied to Nador lagoon (Morocco).

Finally, after the general conclusion, future perspectives and recommendation, cited references are listed.

The scientific outcomes of this thesis are presented as following.

- This first chapter of the third part, represent the outcome of two scientific papers:

- (1) The first paper is a journal article published in the *Frontiers in Environmental Sciences* journal with the title “**Social-Environmental Analysis for the Management of Coastal Lagoons in North Africa**” and under the special issue “Ecosystem Services, Biodiversity and Water Quality in Transitional Ecosystems”.

- (2) The second paper is a proceeding paper published in the *ACM International Conference Proceeding Series* with the title “**Environmental Conditions, Vulnerabilities and Future Perspective of Coastal Water Bodies in Morocco**” under the “*GEOIT4W-2020: Proceedings of the 4th Edition of International Conference on Geo-IT and Water Resources 2020*” .

Furthermore, parts of this chapter have been presented as oral communication in different conferences: (a) “The 8th European Coastal Lagoons Symposium, Athens, Greece, 2018” ; (b) “The 4th Young Scientist Conference in Conservation Sciences in Mediterranean Region, Arles, France, 2018” ; (c) “The Water and Coastal Management Winter School, Faro, Portugal 2019 and 2020”; “The 4th Edition of International Conference on Geo-IT and Water Resources 2020, El Hoceima, Morocco”.

- The second chapter of the third part represent the outcome of a journal article published in the *Remote Sensing* journal with the title “**Contribution of Remote Sensing Technologies to a Holistic Coastal and Marine Management Framework a review**” and belongs to the special issue “*Earth Observation and Sustainable Development in Marine and Freshwater Systems*”. Furthermore, parts of this chapter have been presented as oral communication in different conferences: (a) “The 9th EUROLAG conference on coastal lagoons and transitional environments, Venice, Italy, 2020”; (b) “All-Atlantic Research Forum, Brussels, Belgium, 2020”; and (c) “The Water and Coastal Management Winter School, Faro, Portugal 2020”.

PART 1: COASTAL AND MARINE ENVIRONMENT & CASE OF COASTAL LAGOONS

As defined by the International Geosphere Biosphere Programme (IGBP) via its Land Ocean Interactions in the Coastal Zone (LOICZ) program, the coastal zones are generally defined as transition zones between the land and the ocean (Cracknell, 1999), while the marine areas encompass the salty water in the earth known as seas and oceans.

Costal and marine environment are considered as a major provider of goods and services represented by significant natural resources that are of great financial significance and represent an important economic asset for countries, such as food, renewable energy, natural resources, healthy climate, transport and recreations. Their biodiversity on fauna and flora forms a complex ecosystem. For instance, coastal zones occupies 18% of the global surface in earth where approximately a quarter of global primary productivity occurs and where approximately 60% of the human population lives (Jiang, 2016). Besides the various advantages provided by the coastal and marine environments, the intense exploitation of their natural resources has to a degradation of these ecosystems. This, has led countries to take action for the conservation and sustainable management of these valuable environments.

They are different types of coastal and marine ecosystems that could be found world-wide, such as estuary, fjord, beach, lagoons, sea, forest, deltas, islands, and many others.

CHAPTER 1: COASTAL LAGOONS ENVIRONMENTS

Lagoons constitute 13% of coastal regions globally, range in area from $< 0.01 \text{ km}^2$ to $> 10,000 \text{ km}^2$ (Kjerfve, 1994; Anthony *et al.*, 2009). They are dynamic ecosystems and their morphology is continually changing in response to various processes operating at different rates. Given the confusion associated with the respective descriptions of a lagoon and the necessity to define precisely the object of this research, there is a need to provide some background definitions and characteristics of a lagoon.

I. Lagoons definition

Several definitions of coastal lagoons have been proposed, (LANKFORD, 1977) broadly defined a lagoon as “*a coastal zone depression below MHHW [mean higher high water], having permanent or ephemeral communication with the sea, but protected from the sea by some type of barrier*”.

The most adopted in literature is the one of (Kjerfve, 1994) who defined a coastal lagoon as “*a shallow coastal waterbody separated from the ocean by a barrier, connected at least intermittently to the ocean by one or more restricted inlets, and usually oriented shore-parallel*.” This definition is similar to the ones provided by (Phleger, 1969) and (Barnes, 1980).

A subsequent modification to this by (Bird, 2008) provides some additional insight as to the most likely mode of lagoon formation and the typical nature of the enclosing barrier: “*Coastal lagoons are areas of relatively shallow water that have been partly or wholly sealed off from the sea by the deposition of spits or barriers, usually of sand or shingle, built up above high tide level by wave action*”. However, this definition excludes lagoons enclosed by coral reefs, either within atolls or between fringing or barrier reef and the mainland, because these are essentially marginal marine environments linked with the open sea at high tide

In Europe, the Water Framework Directive (WFD) includes lagoons in the transitional water category and defines them 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). According to (Tagliapietra and Ghirardini, 2006) this definition of Transitional Water (TW) including “lagoons” and adopted by the WFD appears to be an over-simplification, *e.g.* Mediterranean coastal lagoons which, for climatic reasons, are not ‘*substantially influenced by freshwater flows*’ cannot be considered ‘*TW*’. This can create problems for Mediterranean scientists and policy-makers

who, by law, have to produce water typologies according to the WFD (Tagliapietra and Ghirardini, 2006).

This thesis uses the definition of (Kjerfve, 1994) with respect to the full review of (Tagliapietra and Ghirardini, 2006) which represent the case of the south Mediterranean lagoons that is similar to the north Mediterranean lagoons.

II. Physical, climatic and hydrological characteristics of a lagoon

II.1. Physical characteristics of the shape

Coastal lagoons generally have an average less than 2m in depth, they are shallow and well mixed by a wave and current actions (Whitfield, 2011; Kennish and Kennish, 2016) and they are often sub-divided into “choked”, “restricted” and “leaky” (Kjerfve, 1994) (Fig.1):

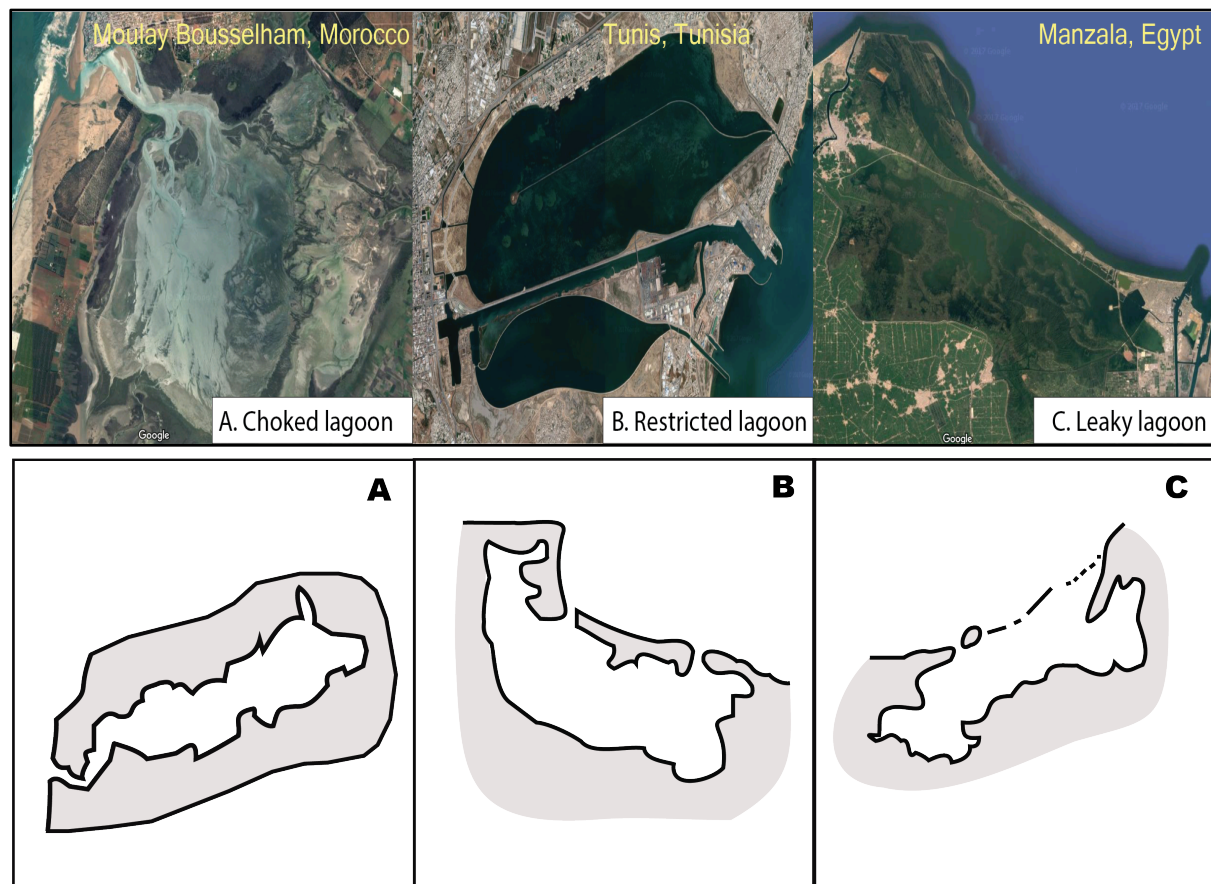


Figure 1: *Geomorphic types of lagoons*

- **Choked Lagoons:** usually consist of a series of connected elliptical cells, connected by a single long narrow entrance channel, along coasts with high wave energy and significant littoral drift. The Moulay Bousselham lagoon in Morocco is an example (Fig.1.A).

- **Restricted lagoons**: consist of a large and wide water body, usually oriented shore-parallel, and exhibit two or more entrance channels or inlets. The Tunis lagoon in Tunisia is an example (Fig.1.B).

- **Leaky lagoons**: are elongated shore-parallel water bodies with many ocean entrance channels along coasts where tidal currents are sufficiently strong to overcome the tendencies by wave action and littoral drift to close the channel entrances. The Manzala lagoon in Egypt is an example (Fig.1.C).

II.2. Climatic and hydrological factors

Lagoons exist in several climatic zones along the coast of the world. The local meteorological conditions strongly influence water temperature and other physicochemical parameters in coastal lagoons (Whitfield, 2011). These water bodies are very responsive to meteorological conditions, notably air temperature because they are very shallow. The climate determines the hydrological balance through direct precipitation on the basins and evaporation, and by influencing freshwater availability from rivers (Tagliapietra and Ghirardini, 2006)

Many of these ecosystems are influenced by river mouths (Pérez-Ruzafa *et al.*, 2013) but they are partly or totally saline as a result of their proximity to coastal waters.

The salinity of coastal lagoons can vary from that of freshwater to hypersaline depending on local climatic conditions and the extent of hydrological connectivity (Kjerfve, 1994).

Many shallow lagoon systems have relatively long water residence times, nutrient inputs can be recycled many times before they exit to the coastal ocean (Whitfield, 2011). Lagoons in North Africa are an example for this situation.

II.3. Tidal range

The tidal range determines a series of important features such as sediment dispersal patterns and sediment texture, morphology and residence time (Tagliapietra and Ghirardini, 2006).

(Hayes M.O., 1979) classified tidal ranges as:

- Microtidal < 1 m
- Low-mesotidal: 1.0 - 2.0m.
- High-mesotidal: 2.0 - 3.5 m.
- Low- macrotidal: 3.5 - 5.0m.
- Macrotidal, >5.0 m

Microtidal low coasts offer the best probability for coastal lagoon development, allowing the formation of sedimentary barrier islands whilst maintaining the persistence of sea-inlets and cyclical water exchange with the sea through the action of tidal currents, whereas in the absence of tides, sedimentation tends to close connecting channels, eventually impounding the lagoons (Tagliapietra and Ghirardini, 2006).

For these reasons and because the virtually tideless Mediterranean Sea, (Tagliapietra and Ghirardini, 2006) suggested to introduce a subdivision of the microtidal into :

- Nanotidal : < 0.5m (e.g. Bardawil ‘Egypt’).
- Microtidal 0.5 - 1.0m (e.g. Boughrara ‘Tunisia’)

Lagoons in North Africa also include mesotidal Atlantic lagoons (e.g. Moulay Bouselham ‘Morocco’).

III. Geological characteristics of a lagoon

From the geological point of view, lagoons are ephemeral environments that are progressively filled in with sediment (Pickett, 1984). They form, develop, and infill within a short geological and many hypothesis suggested that lagoons can be considered as effects of events or processes on generally prograding coasts (Pickett, 1984; Bird, 1994; Cooper, 1994; Osadczuk, 2014).

Most known worldwide lagoons such as the North African lagoons, are relatively young features (Fig.2), that have formed over the last 5-8 thousand years during the sea level rising, and due to the sedimentation process, they are often short lived over geological timescales (Phleger, 1981; Martin and Dominguez, 1994). Thus, their geological evolution is usually expressed regarding the rate of basin filling by sedimentation (Carrasco et al., 2016), that is related to rates of sea level rise (Martin and Landim Dominguez, 1994).

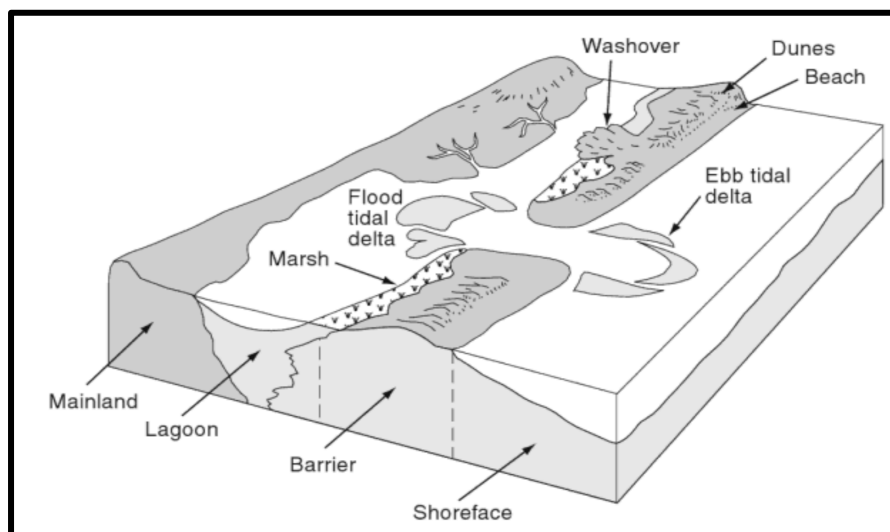


Figure 2: Major geological features of coastal lagoon environment (Cooper, 2009).

(Adlam, 2014) presented a hypothesis of two distinct phases of geologic evolution of coastal lagoons, that are controlled by changes in physical processes.

The early phase suggests the conventional outlook of supply-limited sedimentation that ends when a depth threshold is reached (Fig. 3a). The late phase constrained by the local energy regime and other additional factor that only process when lagoons surfaces are reduced and which act to prevent the sedimentation process (Fig. 3b).

The geological evolution model proposed by (Adlam, 2014) illustrates the two phases and the threshold between the two which is relates to depth (Fig. 3c). This threshold represent the depth at which the orbital movements of the wind waves become able capable of suspending the sediments within the central mud basin (Adlam, 2014)

A model of geologic evolution of coastal lagoons is proposed here and, it is hoped, will be the subject of thorough testing and validation in the future. The model consists of two distinct phases of evolution: the first reflects the traditional view of supply-limited sedimentation (Fig. 3a); whereas the second is constrained by additional factors that act to prevent sedimentation (Fig. 3c). The threshold between the two relates to depth and it is defined as the depth at which the orbital motions of wind waves are able to suspend sediments within the central mud basin (Fig. 3b).

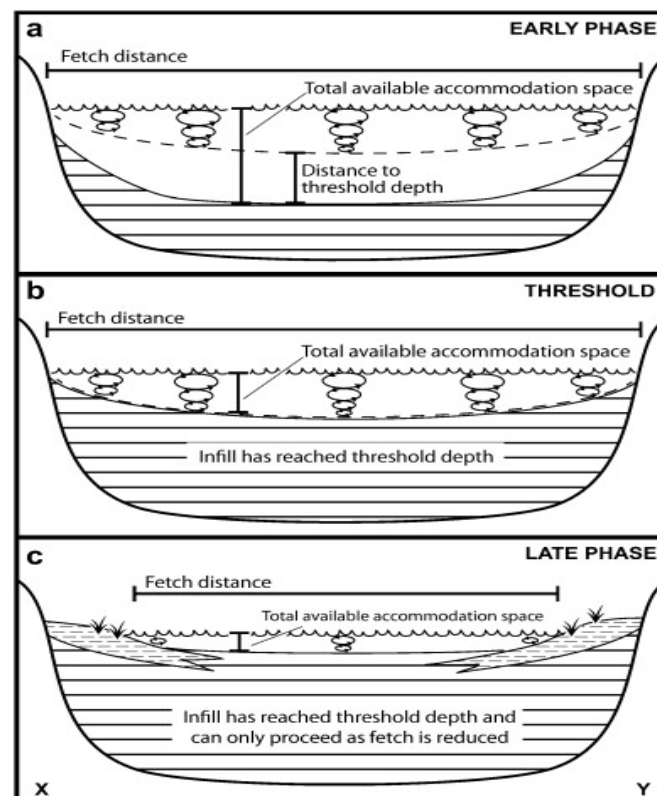


Figure 3: Schematic, cross-sectional representation of the geological evolution of coastal lagoons proposed by (Adlam, 2014).

Furthermore, (Roy *et al.*, 2001) suggested the introduction of the term ‘maturity’ that needs to be considered for lagoons. ‘Mature lagoons’ are entirely filled by sediment; the volume is fully exhausted and fluvial discharge flows to the coasts. While ‘Immature lagoons’ are the ones that are newly inundated basins where the entire volume of water body can accommodate sediment. Moreover, they are different operating process within lagoons that affect the maturity rates such as the sea level rise that can creates a new space to accommodate sediment while reducing while reduced sediment supply can affects this rate (Nichol *et al.*, 1994; Adlam, 2014).

IV. Ecological characteristics of a lagoon

From an ecological perspective, lagoons are complex characterised by a natural high spatial and temporal variability (Newton *et al.*, 2014). These ecosystems are dynamic and highly productive ecosystems, typically 10-15 times more so than continental shelves (Valiela, 2015), that yield a broad range of natural services (Anthony *et al.*, 2009). Many lagoons have been designated as Ramsar sites (Schuyt and Brander, 2004). They contribute to the overall productivity of coastal waters by supporting a variety of habitats, including salt marshes, seagrasses (*e.g.* Moroccan lagoons), and mangroves. They also provide essential habitat for many fish and shellfish species (*e.g.* Nador and Oualidia lagoons in Morocco).

The environmental characteristics and especially the condition of the fauna and flora of the lagoons are very important factors for their fishery and aquaculture function (*e.g.* Bizerte lagoon in Tunisia) (see Tab.1). Because of their relatively low flushing rates, coastal lagoons are favourable habitats for primary producers, such as phytoplankton and aquatic plants (Anthony *et al.*, 2009). Nutrients are transported to lagoons from surface water and groundwater flows and through exchange with the ocean (Pérez-Ruzafa *et al.*, 2013).

In the Atlantic-Mediterranean region including North Africa, these environments house a high biodiversity. More than 621 species of macrophytes and 199 of fish are present in coastal lagoons (Pérez-Ruzafa *et al.*, 2011).

These characteristics lead to ecosystems that maintain a high biological productivity. However, lagoons are particularly prone to pollution due to their restricted circulation (Bartoletti, Bertonati and onnilli, 1985; Tett *et al.*, 2013; Newton *et al.*, 2014).

V. Ecosystem services of a lagoon

Coastal lagoons provide ecological services by protecting coastal watershed areas, buffering the infrastructure from the damaging effects of storms, floods, and erosion.

Many marine species of recreational and commercial importance spend at least a portion of their life cycles in lagoons and adjoining coastal wetland habitats (Whitfield, 2011). Aside from the value of their fisheries, coastal lagoons are used by humans for aquaculture, electric power generation, biotechnology, airports, salt pans, ponds, marinas, shipping, maritime transport, tourism and many other human uses (Joyeux and Ward, 1998; Gönenç and Wolflin, 2005; Whitfield, 2011; Newton *et al.*, 2014, 2018). Together, these industries inject billions of dollars into the economies of coastal regions worldwide.

VI. Human pressures on lagoons

Coastal lagoons are highly susceptible to human activities, and many now rank among the most heavily impacted aquatic ecosystems on Earth. They have been heavily modified by anthropogenic intervention in large numbers worldwide (Evans, 2008) and they are affected by natural habitat alteration both in adjoining coastal watersheds and in the water bodies themselves (Whitfield, 2011). Thousands of pollutants that affect the aquatic environment have long been a concern and cause of research (Fig.4). This number grows annually since new compounds and formulations are synthesized

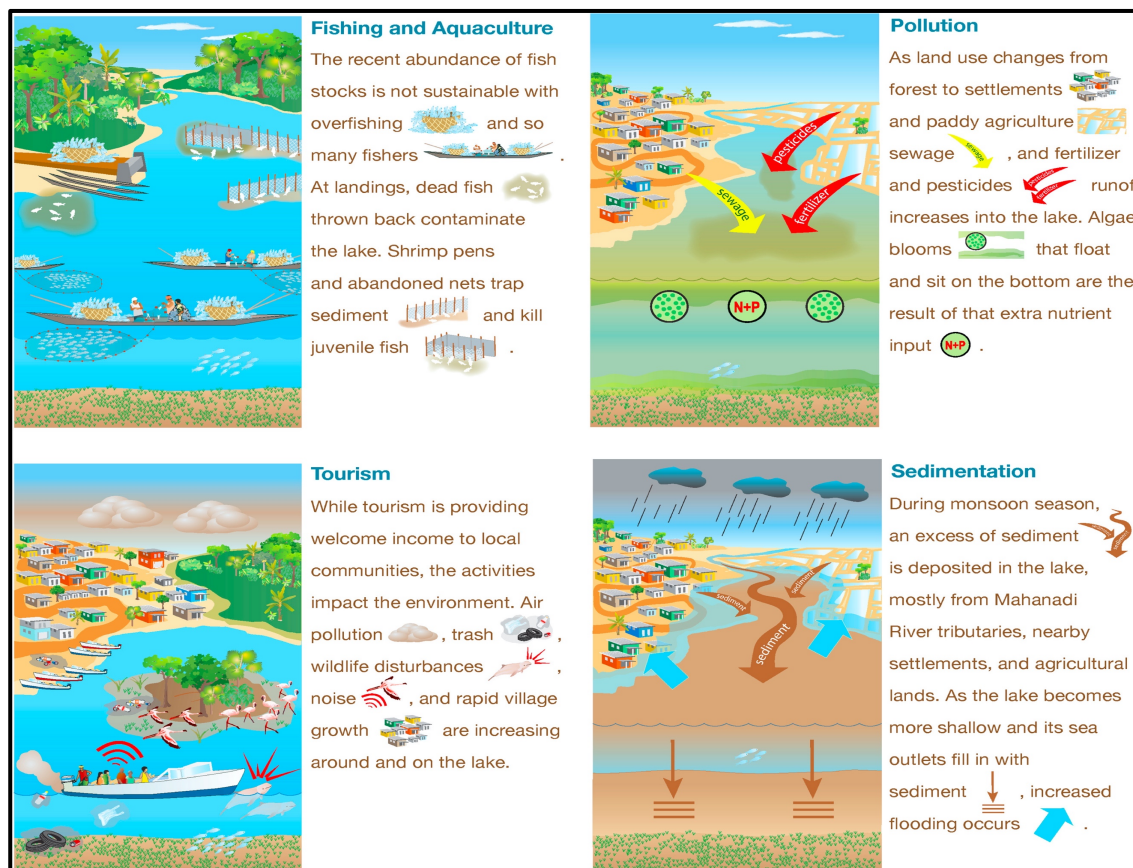


Figure 4: Conceptual diagram of major anthropogenic human pressures and their impact on lagoons (Example of Chilika lagoon in India) (Ramesh et al., 2015)

VII. conclusion

Coastal lagoons are important zones for life between the land and the sea. They are one of the most productive environments and deliver ecosystem services (ES) that provide many ecological, cultural and socio-economic benefits, supporting a range of natural services that are highly valued by society. However, there are different variations related to physical, climatic, geologic, ecologic and social-economic factors, such as the case of North African lagoons.

CHAPTER 2: NORTH AFRICAN LAGOONS

Lagoons in North Africa are heavily populated and have a long history of human occupation and utilisation (Ramdani *et al.*, 2001; Thompson and Flower, 2009; Trigui *et al.*, 2012). These socio-ecological systems cover wide geographical distribution extending from the Atlantic Ocean along the western coastline of Morocco to the southern coastline of the Mediterranean Sea through Morocco, Algeria, Tunisia, Libya and Egypt.

Many of these environments are important for the conservation of habitats and they are under protection from international conventions regarding their natural environment and mainly for the protection of bird communities, which are listed as a Ramsar sites (Ramdani *et al.*, 2009; Sayoud *et al.*, 2017) <https://www.ramsar.org>.

In common with other regions of the world (Newton *et al.*, 2014), the terminology used for North African lagoons varies from country to country, and even among different regions in the same country that use different dialects and languages. These differences in terminology complicate research into historical knowledge about these lagoons systems. Nonetheless, it has been possible to identify most of the terms needed for this study.

I. Situation of North African Lagoons

North Africa is defined as the Southern Mediterranean Region (SMR) or the North of the African Sahara (Desert). It is an area surrounded by the Atlantic Ocean to the west of Morocco, by the Mediterranean Sea to the north of Morocco as well as the coast of Algeria, Tunisia, Libya and Egypt, and by the Red Sea to the east of Egypt (Fig.5).

There are 22 lagoons in North Africa, 4 along the Atlantic shore of Morocco and 18 along the South Mediterranean Region. They are shallow systems, permanently linked to the sea and regulated by tidal exchanges and fluxes at the sediment interface.

The terminology used for coastal lagoons is extremely varied throughout the world and it hampers the transfer of knowledge (Newton *et al.*, 2014). The vocabulary also changes among North African countries even if they are using the same language (Arabic, Amazigh and the two official foreign languages, French in Morocco, Tunisia and Algeria / English in Libya and Egypt). “Lagune” is the most common French term used in Maghreb countries. Moroccan Arabic dialect includes “Merja” as in Merja zerga Moulay Bousselham and sometimes the term “sebkha”. Others names include “Mar Chica” for Nador lagoon a remnant of Spanish colonisation. In Algeria, “Lac”, which means lake, is used, e.g. “Lac El Mellah”, and also “Ildo” for coastal lakes. Tunisia also uses the French term “lac” such as “lac de Tunis”, “lac

Bizerte”. “Bouhaira” is the Arabic term. Farwa “Island” is the term used for “Farwa lagoon” in Libya or “Jazirat Farwa” which means an island. The term “Bouhaira” is used in most of the Egyptian lagoons, “Bihira” in the eastern part and sometimes using even “Bouhaira El Malha” which means “Salted lake”, but in English, lagoons are still referred to as “lake” such as Burullus or Manzala lake. Moreover, Libya has used “lagoon” for four ecosystems, of which only two can be considered lagoons since Ain Ghazala and El Burdi are coastal inundations.

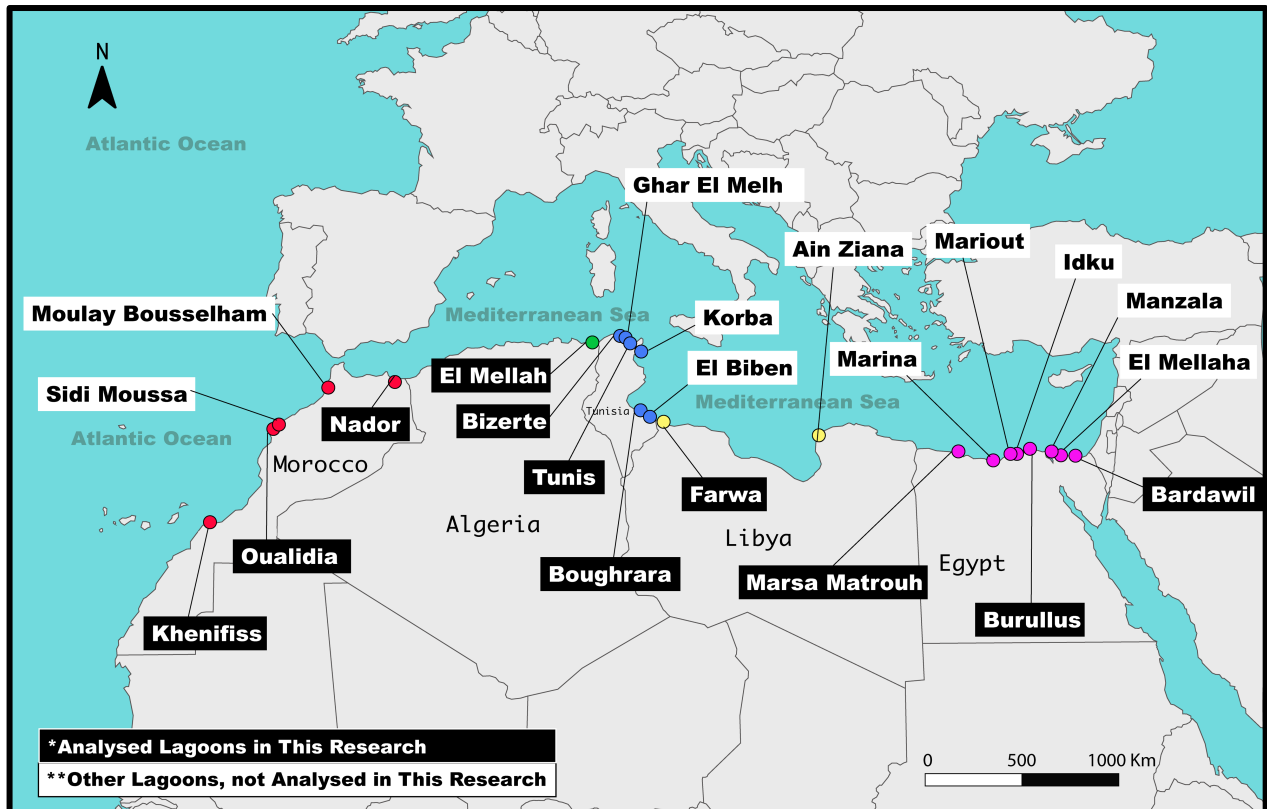


Figure 5: Location of North African lagoons. The lagoon names in white on a black background* were analyzed in detail, those in black on white** were not analyzed. The dots show the lagoons in Morocco (red), Algeria (green), Tunisia (blue), Libya (yellow), Egypt (purple).

I.1. Morocco

Morocco occupies a particular geographical position by its both coasts, Atlantic and Mediterranean sides which extend about 3,500km. This strategic location gives it a diversity of lagoons. The most important one is located in the Mediterranean side which is called Nador lagoon (or MarChica). On the Atlantic coast, it exists four mesotidal lagoons varying on tide from 2 m to 5 m; Moulay Bouselham lagoon (or Merja Zerga), Khnifiss lagoon, Sidi Moussa lagoon and the Oualidia lagoon (Fig.6). Theses lagoons varies in size, physical, ecological and geological features.

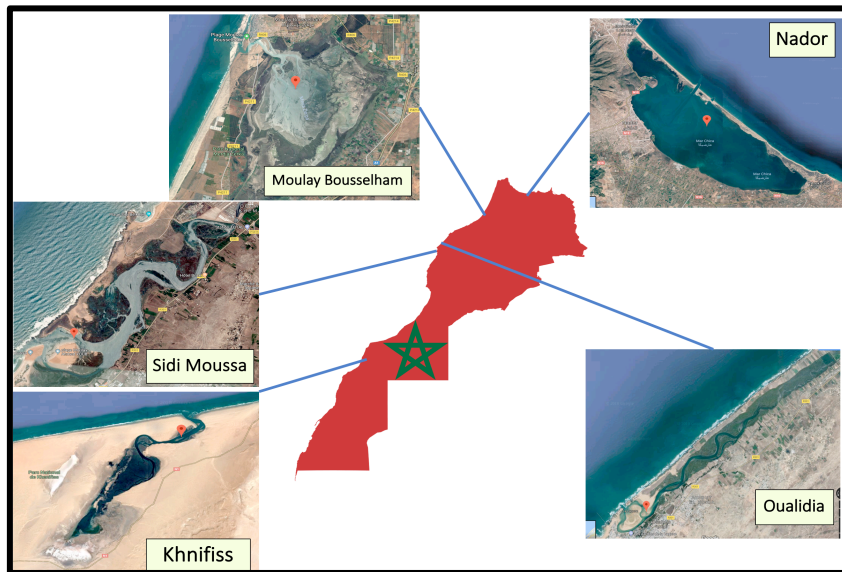


Figure 6: Moroccan lagoons (Khnifiss, Sidi Moussa, Oualidia, Moula Bouselham, Nador)

I.2. Algeria

Algeria is the largest country in Africa and comprises a long coastline of 1622 km on the South Mediterranean Sea that receives several rivers flows. 45% of this Algerian population is concentrated along the coastline on a very narrow strip, mainly in harbours and industrial areas where most of economic activities are situated (Grimes, 2003). This situation exerts excessive pressures on the coastal ecosystems of the countries, and affects their environmental state and conditions. This Algerian coast presents different morphological patterns with a majority of rocky shores, including high cliffs, and also sandy dunes and beaches (Ahmed *et al.*, 2018).

Despite the different ecosystems existing along the Algerian coastline, the El Mellah lagoon remains to be the only existing coastal lagoon (Fig.7).

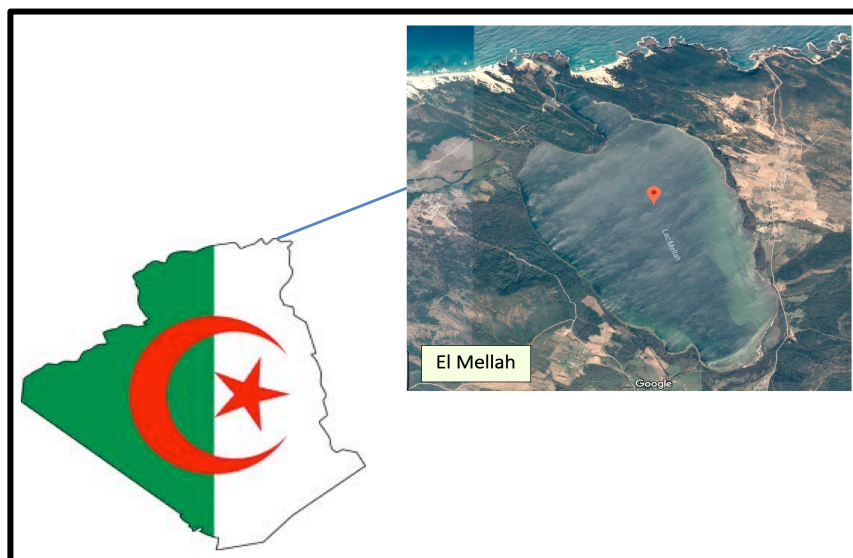


Figure 7: El Mellah lagoon (Algeria)

I.3. Tunisia

Situated in a Mediterranean climatic region, bordered by Algeria on the West and Libya on the South-East, Tunisia has a coastline of 1,148 km with an abrupt southward turn on its coast which gives it two distinctive lines, West-East in the North part and North-South in the East part (Fig.8). The weather is hot and dry in the summer, cooler and rainfall in the winter (Ismail et al., 2018). Relative previous sea-level rise were prevailed in the Holocene geological time, along most of the Tunisian coasts (Paskoff and Sanlaville, 1983).

Tunisia has six lagoons, three in the north part of the country (*Bizerte*, *Ghar el Maleh* and *Tunis*) and three lagoons in the East part of the country (*Korba*, *Boughrara* and *Biban*). These lagoons differ considerably regarding their physical and ecological settings.

For this thesis, 3 lagoons were analysed in detail (Bizerte, Tunis and Boughrara).

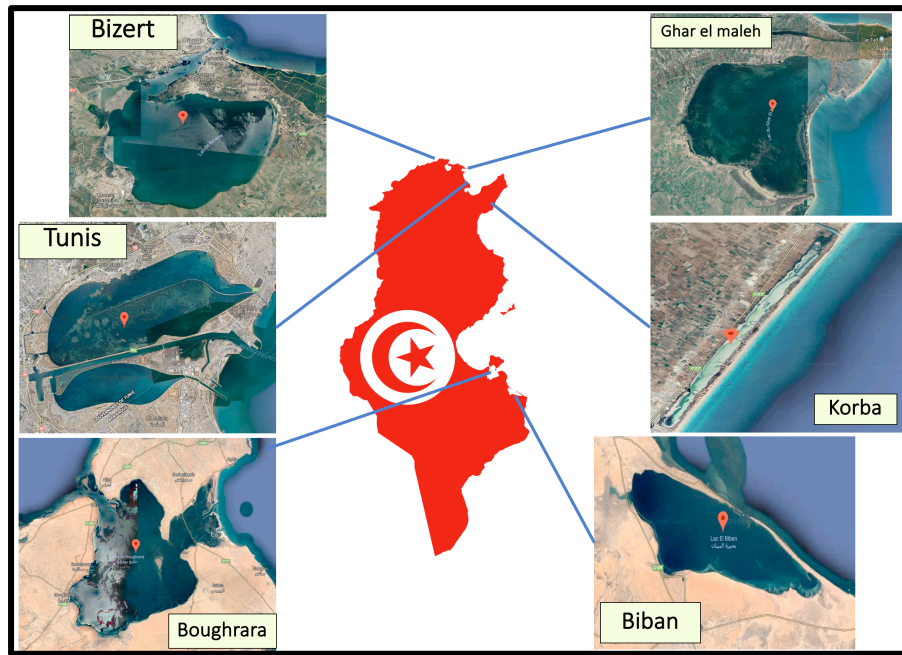


Figure 8: *Tunisian lagoons (Bizert, Ghar el Maleh, Tunis, Korba, Boughrara, Biban).*

I.4. Libya

Libya comprises a coastline of 1770 km bordered by Tunisia from the West and Egypt from the East. Its coast is the less studied one compared to other south Mediterranean countries.

The country has two lagoons; Farwa and Ain Zaina (Fug.18) and two others water bodies considered as lagoons; El Burdi and Ain Ghzala (see (Adam, 1990; Mashud *et al.*, 2006; Hipp, 2011)). For this purpose, we analysed these two systems.

The El Burdi system is not a coastal lagoon but rather a coastal inundation with strong tectonic control. It is not sediment-built as evidenced by the steep rise of the land on all sides (see; Google Earth). The Ain Ghazala system is not a coastal indentation rather than a lagoon in spite of the shallow depths and the surrounding low relief landscape (Fig.9).

The most described Libyan lagoon is Farwa lagoon that was analysed in this study.

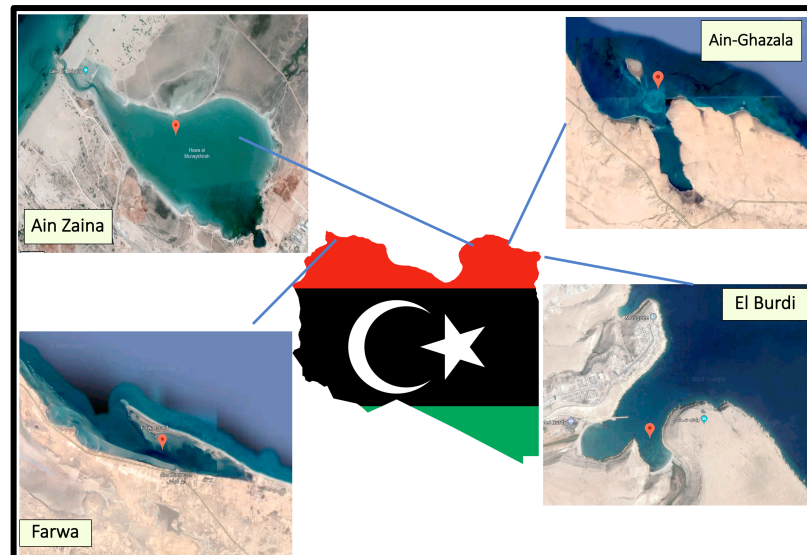


Figure 9: Existing lagoons (Farwa, Ain Zaina) and coastal inundations (Ain-Ghazal, El Burdi) in Libya

1.5. Egypt

Egypt has two coastlines; the Mediterranean Sea coast (called El Sahel El Shamali) which extends for about 1050 km and the Red Sea coast (Called El Sahel El Sharqui) stretching 1250 km.

There are a number of large lagoon along the Mediterranean Egyptian coasts represented by eight micro-tidal to nano tidal lagoons (Marsa Matrouh, Marina, Mariout, Idku, Burullus, Manzala, El-Mellaha and Bardawil) (Fig.10).

Most of coastal plain were lagoons are located, consist of three Pleistocene calcareous ridges which are parallel to the Egyptian coastlines and are separated by different flat-bottomed depression (Torab and Dalal, 2015).

From sedimentological aspects, the ridges sediment related to the lagoons, are composed of well sorted medium grained aragonic ooids sands (Torab and Dalal, 2015)..

Most of dunes separating the lagoons from the Mediterranean sea, are in forms of discontinuous series, which were developed at different distances from the mainland.

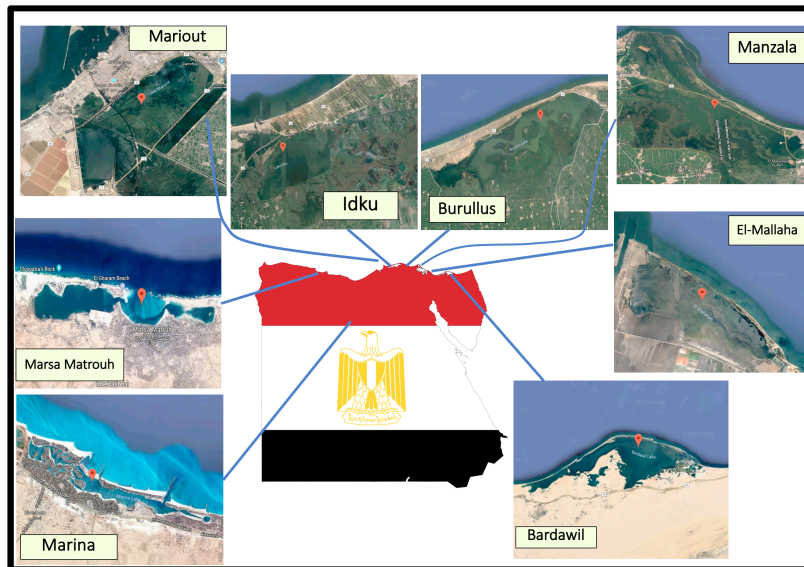


Figure 10: Existing lagoons in Egypt (Marsa Matrouh, Marina, Mariout, Idku, Burullus, Manzala, El-Mallaha, Bardawil)

II. Major Physical and ecological characteristics of North African lagoons

Areas surrounding lagoons in North Africa have a long history of human occupation and utilization (Ramdani et al., 2001; Thompson and Flower, 2009; Trigui et al., 2012). These important social-ecological systems (SES) continue to be heavily impacted by human activities, such as extraction of freshwater and urbanization, as well as the development of economic sectors, e.g. fisheries, agriculture and tourism.

Eight out of thirteen lagoons are choked, three are restricted and two are leaky. They vary in size from 3,5 Km² (Oualidia, Morocco) to 500 km² (Boughrara, Tunisia). The average depth goes from 1,5 m (Moulay Bousselham, Morocco) to 7 m (Bizerte, Tunisia). The minimum neap tide is found in 0,05 (Nadora) and the maxmim spring tide is found in the khenifiss lagoon (3,39 m) which are related to the adjacent sea (Tab.1).

Most of North African lagoons share the same ecological characteristics such as seagrass meadow, special bird habitat and sand dunes (Tab.1).

Furthermore, many of these SES are provided with some legal protection through international conventions, particularly for the protection of bird communities, in the case of Ramsar sites (Ramdani et al., 2009; Sayoud et al., 2017). However, current levels of exploitation are unsustainable and there is an increasing need for an integrated, basin-wide approach to the management of water resources and aquatic ecosystems in the region (Thompson and Flower, 2009). Indeed, there have been recent research projects to improve the understanding of these lagoon ecosystems and their surrounding resources (see Table 2).

Table 1: Major physical and ecological characteristics of North African coastal lagoons

Country		Morocco					Algeria	Tunisia			Libya	Egypt		
Lagoon		Khenifiss	Sidi Moussa	Oualidia	Moulay Bousselham	Nador	El Mellah	Bizert	Tunis	Boughrara	Farwa	Marsa Matrouh	Burullus	Bardawil
Adjacent Sea		Atlantic	Atlantic	Atlantic	Atlantic	Mediterranean	Mediterranean	Mediterranean	Mediterranean	Mediterranean	Mediterranean	Mediterranean	Mediterranean	Mediterranean
Typologie		Chocked	Restricted	Leaky	Chocked	Chocked	Chocked	Chocked	Restricted	Leaky	Restricted	Chocked	Chocked	Chocked
Size (Km²)		65	4,2	3,5	35	115	8,65	150	22	500	32	27	420	519
Avrage Depth (m)		5	2,5	2	1,5	5	3,5	7	1,5	4	2	2	2	1,21
Water Temperature (°C)	Average T	18,5	19,95	19,1	21	19,95	20,95	19	18,55	13	19,9	24,75	19,5	20,5
Precipitation (mm/y)	Average P	41	390	390	366,3	300	649	634,6	500	210	233	137,5	20	90
Tidal Exchange (m)	Neap Tide	1,14	0,3	0,8	0,95	0,05	0,4	0,1	0,09	0,56	0,2	0,12	0,18	0,25
	Spring Tide	3,39	1,8	3,6	2,54	0,36	0,5	0,12	0,26	0,8	0,8	?	0,33	0,35
Freshwater Input	Surface water		SW	SW	SW	SW	SW	SW	SW	SW			SW	
	Groundwater		GW		GW	GW	GW			GW				GW
Ecological Charcteristics	Park	P	P	P	P	P	P				P			
	Ramsar site	R	R	R	R	R	R		R	R	R		R	R
	Special bird habitat	B	B	B	R	B	B			B	SB		SB	SB
	Sea-grass meadows	SGM	SGM	SGM	SGM	SGM	SGM	SGM	SGM		SGM	SGM		SGM
	Salt marsh	SM	SM	SM	SM	SM	SM							.
	Sand dune	SD	SD	SD	SD	SD	SD				SD	SD	SD	SD
	Forested areas					FA	FA	FA						
	Riparian vegetation	RV	RV	RV	RV	RV	RV						RV	RV

III. State of knowledge of North African lagoons

Lagoons in North Africa are heavily populated and have a long history of human occupation and utilisation (Ramdani *et al.*, 2001; Thompson and Flower, 2009; Trigui *et al.*, 2012). These socio-ecological systems cover a wide geographical distribution on the Atlantic Ocean along the west coastline of Morocco and the southern Mediterranean Sea comprising Morocco, Algeria, Tunisia, Libya and Egypt. Many of the North African lagoons are important for the conservation of habitats and they are under protection from international conventions regarding their natural environment and mainly for the protection of bird communities, which are listed as a Ramsar sites (Ramdani *et al.*, 2009; Sayoud *et al.*, 2017) <https://www.ramsar.org>. The need to use these lagoons and their neighbouring landscapes for freshwater, fisheries, urbanisation, agriculture and even tourism has often led to unsustainable resource use by a human. And given their position at the downstream ends, they are intensely sensitive to alterations as a result of the activities and the pressures. Furthermore, the application of integrated, basin-wide approaches to the management of water resources and aquatic ecosystems in the region was advocated (Thompson and Flower, 2009).

Having recognised the necessity to improve understanding of the functioning of North African lagoons, numerous recent projects (Fig.11) dealing with these ecosystems and their surrounding resources were represented and improved knowledge of the current situation (CASSARINA, COLASU, MELMARINA, MEDINA and MAGHLAG “START”) (Tab.2).

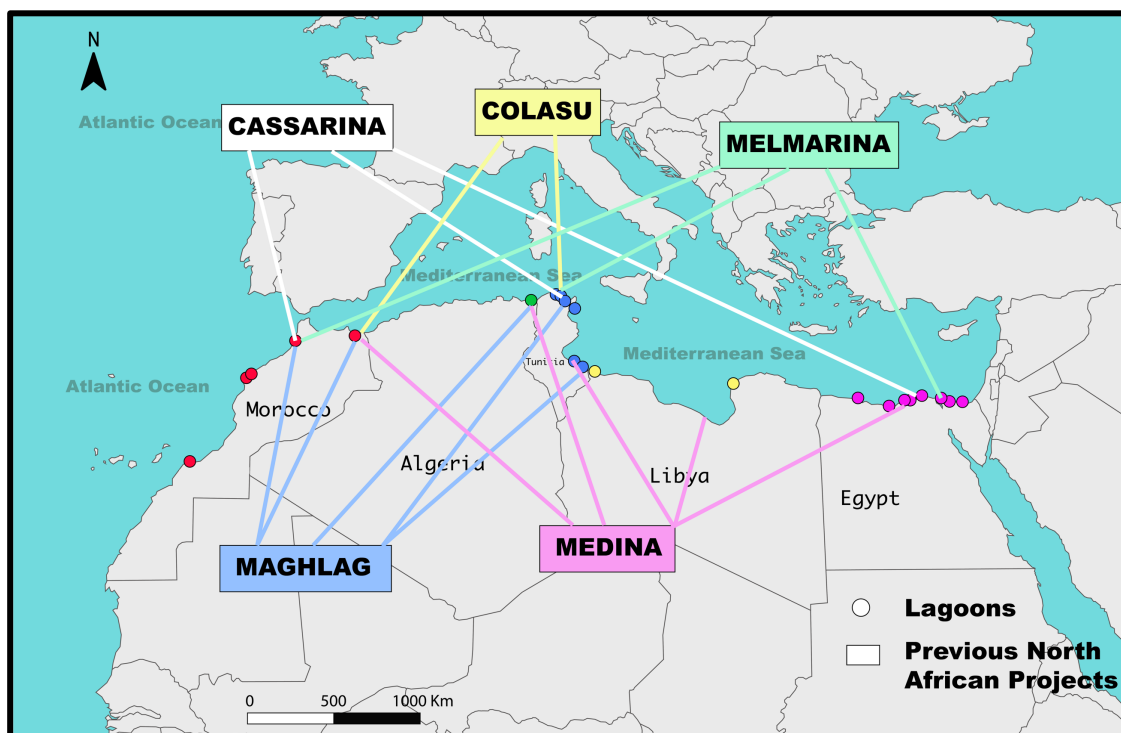


Figure 11: Previous North African projects dealing with lagoons and other ecosystems

III.1. CASSARINA

The **CASSARINA** project (IC18CT960029): named “*Change, stress and sustainability - aquatic ecosystem resilience in North Africa*” ftp://ftp.cordis.europa.eu/pub/inco/docs/westlands/01_cat96029_cassarina21_en.pdf. They were Multi-disciplinary studies on lakes and lagoons undertaken by scientists from North African countries (Morocco, Tunisia and Egypt) working in co-operation with colleagues from Europe (the United Kingdom and Norway) (Flower, 2001).

The aims were :

- (1) To assess the impact of land-use practices and changes on nine North African lakes and lagoons in Morocco (*Moulay bousselham ‘Merja Zerga’, Sidi Bou Rhaba*) , Tunisia (*Ichkeul, Chitane, Bokka*) and Egypt (*Burullus, Manzala, Korba, Edku*) with an integrated multi-disciplinary approach.
- (2) To establish their ecological baselines and pre-disturbance communities,
- (3) To investigate reactions to 20th century human influences on their ecosystems (Birks *et al.*, 2001),
- (4) To implement and integrate regional monitoring of aquatic organisms and water quality with centrally imposed analytical quality control and finally,
- (5) To establish internationally co-ordinated protocols for future monitoring.

These wetlands and lowland lakes and lagoons were being lost at an alarming rate as a result of increasing human demands for water and land, paralleling to regional population growth (Ramdani *et al.*, 2001). The nature and consequences of these ecosystems’ disturbances were poorly understood at that time and effective environmental monitoring programmes for most sites was virtually non-existent.

A combination of modern survey and paleolimnological techniques were employed to help set ecological baselines for the late 20th century and to reconstruct past environmental changes at each of the nine sites during the 20th century. Also, a corresponding sampling of water quality, phytoplankton, zooplankton and fish and the monitoring of fixed littoral vegetation transects for each lake and lagoon as well as a collection of sediment cores for palaeoecological analysis. Moreover, they use sediment core chronologies based mainly on radio-isotopes (210Pb and 137Cs) and analysis of the sedimentary remains of aquatic biota (diatoms, zooplankton, higher plants and benthic animals), however, information on the status of these nine sites and the rates

and directions of trends in environmental change over recent decades were generally lacking. Especially, regional data on the inputs of atmospheric pollutants to these sites were absent (Rose, Flower and Appleby, 2003).

Salinization, siltation, chemical contamination and land-use amplification were the major elements that downgrade water quality and affecting the biological diversity. These modifications were interpreted in terms related to biodiversity issues and to water quality alteration.

The Project has demonstrated remarkably fast responses by the lakes and the lagoons to environmental pressures. In particular, it highlights the hazards to these North African ecosystems if uncontrolled utilization continues.

III.2. COLASU

The **COLASU** project (ICA3-CT-2002-10012-COLASU): named “*Sustainability of Mediterranean coastal lagoon ecosystems under semi-arid climate*” (https://cordis.europa.eu/project/rcn/64910_en.html).

The aim was defining the issues of two protected coastal lagoons in of both El Melah Lagoon (Tunisia) and Nador Lagoon (Morocco) that were subjected to pollutions (F. Ruiz *et al.*, 2006) due to anthropogenic activities such as wastewater, agriculture and also to the natural actions. It was proposed to understand the morphodynamic and the geochemical evolution of the lagoons, determine their types and origin of pollution and their behaviour in the physical environment, also to assess the development strategy reducing the pollution risks to safeguard the ecosystems. Additionally, the project made it a priority to defines the issues relevant to sustainable lagoon management in active and direct consultation with all actors and to produce guidelines and recommendations in order to help public authorities in the decisions towards sustainable development.

III.3. MELMARINA

The **MELMARINA** Project (ICA3-CT-2002-10009): named “*Monitoring and Modelling Coastal Lagoons: Making Management Tools for Aquatic Resources in North Africa*” http://cordis.europa.eu/project/rcn/67460_en.html . It was funded through the EU INCO-Med programme.

This proposed project concerned the development of an ecosystem monitoring in three North African key sites; Merja Zerga (Morocco), Ghar El Melh (Tunisia) and Lake Manzala (Egypt),

which have a long history of human occupation and exploitation (Ayache *et al.*, 2009; Ramdani *et al.*, 2009; Thompson and Flower, 2009). The monitoring plan used a field survey, long-term monitoring through field equipment, remote sensing technologies and their combination of hydraulic/ecological modelling.

The chosen lagoons where demands for water continued to grow whilst the impacts of climate change and sea level rise will increase, the environment has been intensely impacted particularly during the twentieth century, not only from the biodiversity features that were at risk in these ecosystems but the goods and services that affect human welfare were similarly in decline.

Becoming aware of future changes in these environments, scientists involved in the MELMARINA projects built many objectives, such as:

- (1) To develop early warning tools and decision support systems that assess the aquatic resources of some North African lagoons and the environmental health of their surrounding areas.
- (2) To establish and evaluate long-term research on monitoring, measuring and modelling sustainable development in these lagoons.
- (3) To evaluate and model the influence of human activities on water distribution quantity and quality.
- (4) To promote commonality in research methodology through information exchange and by instigating training programmes for young scientists within North African associate institutions in specialist areas of aquatic resource monitoring and modelling.
- (5) Finally, to forge active connections with other international and national organisations concerned with the management of marine resources (principally on lagoons) and to exploit further the outcomes of the project by extensively disseminating results.

As results of the projects; all lagoons were affected to some extent by excess nutrients (Ramdani *et al.*, 2009). The Manzala (Egypt) lagoon produced a rich phytoplankton community dominated by green algae due to high inflows of both freshwater and nutrients inputs. In Merja Zerga (Morocco) and Ghar El Melh (Tunisia) lagoons, diatoms frequently predominated by phytoplankton during the summer period.

The examination of the ecological and biological status of fisheries in three sites showed they were controlled by variations in fishing activities, local environments and periodic conditions. A decrease in fish production was noted and it attributed to declining ecological conditions.

Many causes were implicated comprising sea interaction troubles, decrease of the continental (fresh) water supply and an increase of pollution producing eutrophication. Furthermore, overfishing contributed to fisheries decline (Kraïem *et al.*, 2009).

The remote sensing technologies showed significant changes related to the geomorphological development of all three ecosystems, but the areas of open water and emergent vegetation have been highest in the Manzala lagoon (Ahmed *et al.*, 2009).

The hydrological modelling showed modifications on the water resource. Linkages between water quality, water availability, human activities and biological characteristics of coastal lagoons were discussed with particular reference to the controls upon vegetation (Thompson and Flower, 2009). The form of the modelling was important in the development of mitigation measures in the face of climate change and sea level rise.

The MELMARINA Project has provided the foundations for the sustainable management of these aquatic resources (Flower and Thompson, 2009).

III.4. MEDINA

The MEDINA Project (282977): named “*Marine Ecosystem Dynamics and Indicators for North Africa*”. It was designed to enhance Northern African Countries monitoring capacity of their coastal areas ecosystems, including fish stocks resources, and consequently their capacity to implement environmental policies, conventions and protocols.

They were Two main objectives of the MEDINA project:

- (1) To contribute to the implementation of permanent and cost-effective monitoring & assessment programmes of the status of coastal marine ecosystems in North African Countries (Morocco, Algeria, Tunisia, Libya and Egypt), enhancing the monitoring capacity in the region and identifying as well major risks due to climate change, as support to the elaboration of adaptation strategies for their mitigation.
- (2) To ensure the exploitation of the Global Earth Observation System of Systems (GEOSS) and Global Common Infrastructure (GCI) capabilities at the maximum extent possible in providing the appropriate infrastructure for fusion of satellite Earth Observation (EO) and conventional environmental monitoring data.

The project covered all sea area of North Africa (large scale) but five areas, one in each country, were selected as pilot cases (local scale), representing typical ecosystems and issues of concern in the region. The pilot cases, which were chosen in close collaboration with North African

partners were: The *Bay of Bejaia* (Algeria), *Lake Burullus* (Egypt) the *Gulf of Syrte* (Libya), the *Lagoon of Nador* (Morocco), the *Gulf of Gabès* (Tunisia). These areas were chosen to consider their representativeness at the regional level, in terms of ecosystem typology and environmental issues, their social and economic importance and the availability of environmental data.

As results for the local scale: they adapted/developed tools for investigating coastal erosion, nutrients enrichment and eutrophication, fishery decline, sustainable aquaculture, conservation of *Posidonia o.* meadows and the impact of coastal urbanization.

For the regional scale, they developed tools and methodological approaches for supporting the implementation of the main policy for the protection of the Mediterranean marine coastal ecosystems, i.e. the UNEP-MAP, EcAp, endorsed by all Contracting Parties of the Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean (Barcelona Convention).

As a contribution of the project to the GEOSS-GCI; they created a free access portal <http://www.medinageoportaleu/>, which is the main doorway for stakeholders and end-users to exploit the results of the project

III.5. MAGHLAG

The **MAGHLAG** project: named “*Maghrebian lagoons Network*”. It was conducted within the grant of Global Change SysTem for Analysis, Research and Training (START) Initiative.

The scientific community of the project was from North African countries, specifically from the Maghreb region (Morocco, Algeria and Tunisia), they were working in co-operation with partners from Italy, Portugal and Norway. The network discussed the aspect of climate change and its impacts on the ecosystems and the population which had not been addressed before.

Five sites were chosen; *Moulay Bousselham* and *Nador* lagoons in Morocco, *Mellah* lagoon in Algeria, *Ghar El Melh* and *Biban* lagoons in Tunisia (Trigui *et al.*, 2012).

The aim of the project was to deliver a quantitative assessment of the biogeochemical budgets of these five lagoons and a qualitative assessment of their sensitivity and vulnerability in the context of climate change.

Many specific objectives were involved in this project:

- (1) Starting by providing information on the Maghreb lagoons and then their contribution in the whole Mediterranean area.

- (2) Evaluate the biogeochemical budgets of the studied lagoons and their position in terms of the source of nutrients.
- (3) Provide a qualitative assessment of their sensitivity to climate change and find out appropriate policy choices to address the effects.
- (4) Develop the consciousness of the local stakeholders to the ecosystem services provided by lagoons, to the potential effects of climate change on these types of environments and to adaptation plans.

As outputs of the project; The network collected all the available data and information on the studied lagoons; They realised their biogeochemical budgets “LOICZ” that provided important information on water fluxes through the system (residence time), Nutrient fluxes (input, output, source, sink) and the ecosystemic functions linked to the metabolism. But the existing datasets were not exhaustive and with low numbers of replicates.

The main outcomes were in terms of science and policy implications by involving stakeholders, training and capacity building for postgraduate researchers and finally, networking and cooperation at national and international level.

Table 2: *Summary of results of previous lagoons’ North African projects*

Project	Country	Lagoon and other ecosystems	Results of Projects
CASSARINA	Morocco	Moulay Bouselham Sidi Boughaba Lake	Established ecological baseline and explored responses to 20 th century human impact to environmental stresses
	Tunisia	Bokka Lake, Chitane Lake Ichkeul Lake	
	Egypt	Delta Lakes	
COLASU	Morocco	Nador	Characterisation of morpho dynamic process and determination of pollutant elements
	Tunisia	Ghar El Melh	
MELMARINA	Morocco	Moulay Bousselham	Surveys, Monitoring and modelling the lagoons (Hydrology, water, sediment quality and aquatic ecology)
	Tunisia	Ghar El Melh	
	Egypt	Manzala	
MEDINA	Morocco	Nador	Developed and tested tools for water mass classification, scenario analysis, and ecosystem monitoring and assessment at the locale scale
	Algeria	Bay of Bejaia	
	Tunisia	Gulf of Gabes	
	Libya	Gulf of Syrte	
	Egypt	Burullus	
MAGHLAG	Morocco	Moulay Bouselham Nador	Improved cooperation among regional scientist and calling attention to lagoons economic and ecological importance
	Algeria	Mellah	
	Tunisia	Ghar El Melh Biban	

IV. Conclusion

The variety of issues in North African coastal lagoons (ecological functioning, biodiversity, productivity, human uses) require conceptual models to organize, understand, clarify issues and recapitulate information in a standard, logical and hierarchical method (Patrício et al., 2016).

This state-of-the-art includes a range of definitions of coastal and marine environment as a life-driven landscape and as fragile and vulnerable ecosystems in co-evolution. For instance, most of these systems included in the previous projects of North African lagoons fit with the main definition chosen for this thesis

The first part of this chapter explores the definitions that have been applied to lagoons systems with reference to (Kjerfve, 1994) definition with respect to the full review of (Tagliapietra and Ghirardini, 2006). Furthermore, it identified the physical and ecological characteristics of lagoons within their services and human pressures.

The second part comprises the major co-ordinated projects that have been done in the past about North African lagoon (Tab.2). It addressed some of the lagoons within lakes, bays and Gulfs in some projects.

The CASSARINA and MELMARINA Project showed an example of confusing nomenclature between lakes and lagoons. There are many coastal lagoons called “lake ...” (e.g Manzala, Burullus, Edku, Merja Zerga ...) which is the same case in many research papers. Moreover, they compared in the project the lagoons systems and lake systems which are different from each other.

North African lagoons were considered as common in all the countries bordering the southern Mediterranean area (Morocco, Algeria, Tunisia and Egypt) excluding Libyan lagoons in all projects but some of them mentioned the particularities exhibited by each system.

PART 2: CHARACTERISTICS OF NORTH AFRICAINS COASTAL LAGOONS STUDY SITES & METHODOLOGY

CHAPTER 1: STUDY SITES: COASTAL LAGOONS IN MOROCCO, ALGERIA, TUNISIA, LIBYA AND EGYPT

Eleven lagoon sites were selected on the basis of: available data and literature; the importance of their social ecological and economic roles in the chosen countries; their different key environmental characteristics in terms of basin surface, land use distribution, typology, lagoon size, the adjacent sea (Atlantic, Mediterranean), dynamics and climate. The 11 coastal lagoons include: Khenifiss and Oualidia (Morocco) along the Atlantic shore, and Nador (Morocco), El Mellah (Algeria), Bizerte (Tunisia), Tunis (Tunisia) and Boughrara (Tunisia), Farwa (Libya), Marsa Matrouh (Egypt), Bardawil (Egypt) and Burullus (Egypt) along the Mediterranean shore (Fig.12).

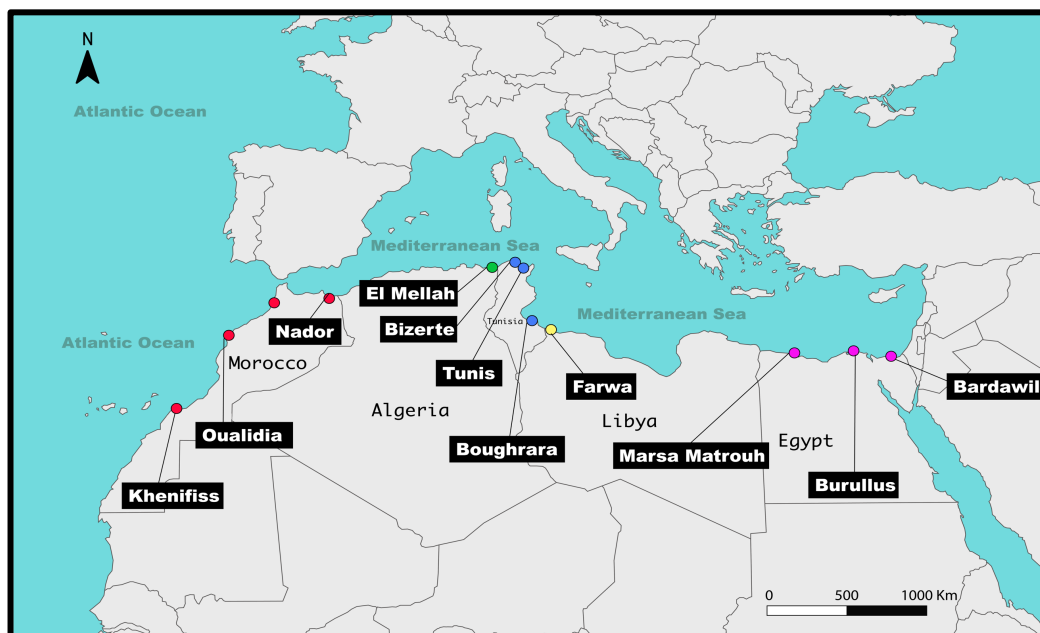


Figure 12: Study sites (North African lagoons)

I. Morocco

I.1. Khenifiss Lagoon (Atlantic side)

The Khenifiss Lagoon is a Moroccan national park (Sánchez Piñero et al., 2009) and registered as World Heritage by Unesco, located on the south of Morocco near Tarfaya city and occupied 65 km² (Fig. 13). It is a choked lagoon, opened to the Atlantic shore by a narrow inlet called “Foum aguitir” (Foum = Mouth), with a length of 20 km and a width of 4km in the centre of the lagoon (Fig.13). The climate is Saharian, with 45–70 mm mean annual precipitation and 18,5 °C as an average of water temperature (Lefrere *et al.*, 2015). The average depth is 5m and has no freshwater input. The current morphology of the khenifiss lagoon system began to develop in the Holocene and continues to the present day (Amri, 1998).

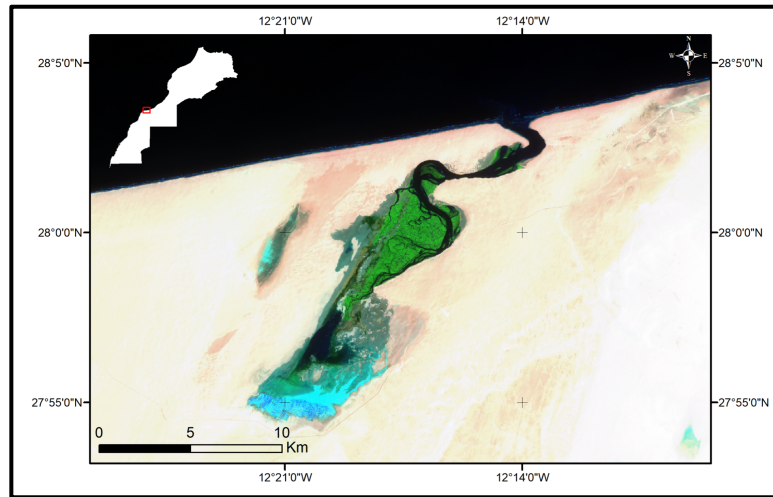


Figure 13: Khnifiss lagoon (Morocco)

This lagoon is part of the Tarfaya Coastal Basin (Fig.14); it corresponds to the northern termination of the vast Western Sahara Basin, which is limited to the NE and E by a major tectonic accident that links Agadir to Cape Timiris (Mauritania), affecting both the Precambrian ranges (Zemmour) and the sedimentary cover (Brebion and Ortlieb, 1976). The marine Pleistocene is very incomplete; the substratum of the coastal platform is essentially composed of Cretaceous marine limestones; and along the coast, the morphological and geological importance of the Moghrebien ‘slab’ calcareous sandstone is noted, The dune field is located on a limestone plateau. This ecosystem is surrounded by giants complex dune systems, showing various features and making it a special and unique system in the world, which exhibiting a strongly red coloured sand with a high size and a particular morphodynamic (Adnani *et al.*, 2018).

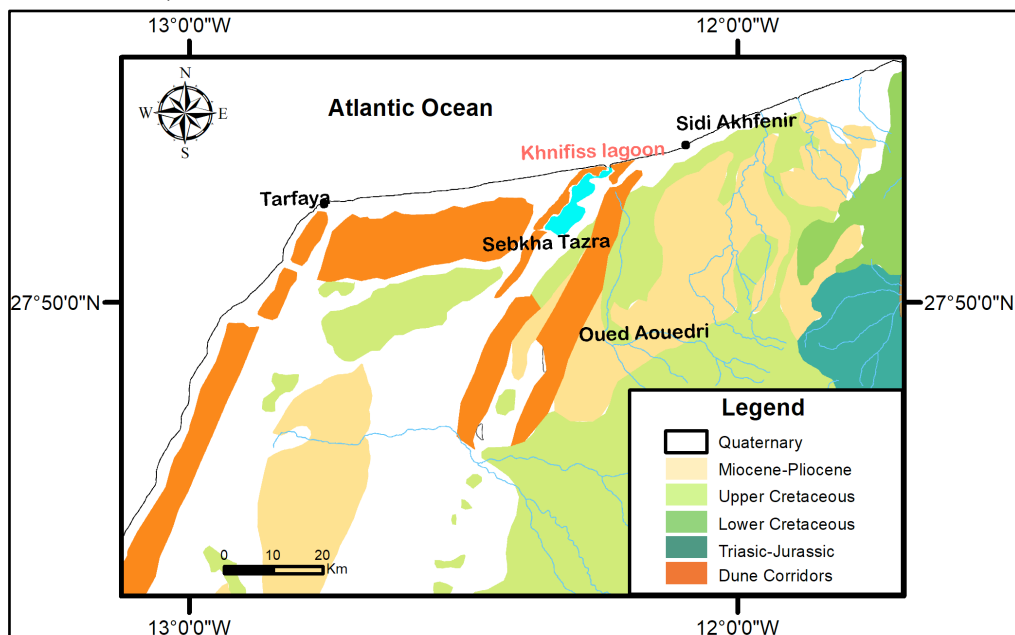


Figure 14: Geological map of the province of Tarfaya (Adapted from Adnani et al., 2018)

I.2. Oualidia Lagoon

The Oualidia lagoon is located in the middle of the Atlantic shore of Morocco in the Oualidia city between the cities of El Jadida and Safi. It occupies an area of 3 km² and it has a ‘snake’ shape parallel to the ocean (Fig.15a). It is a restricted lagoon, connected to the Atlantic shore by two narrow inlets (major and secondary inlets) which allow the water circulation of the lagoon. The length of this ecosystem is 7 km and the width is 0.5 km (Beryouni *et al.*, 2012).

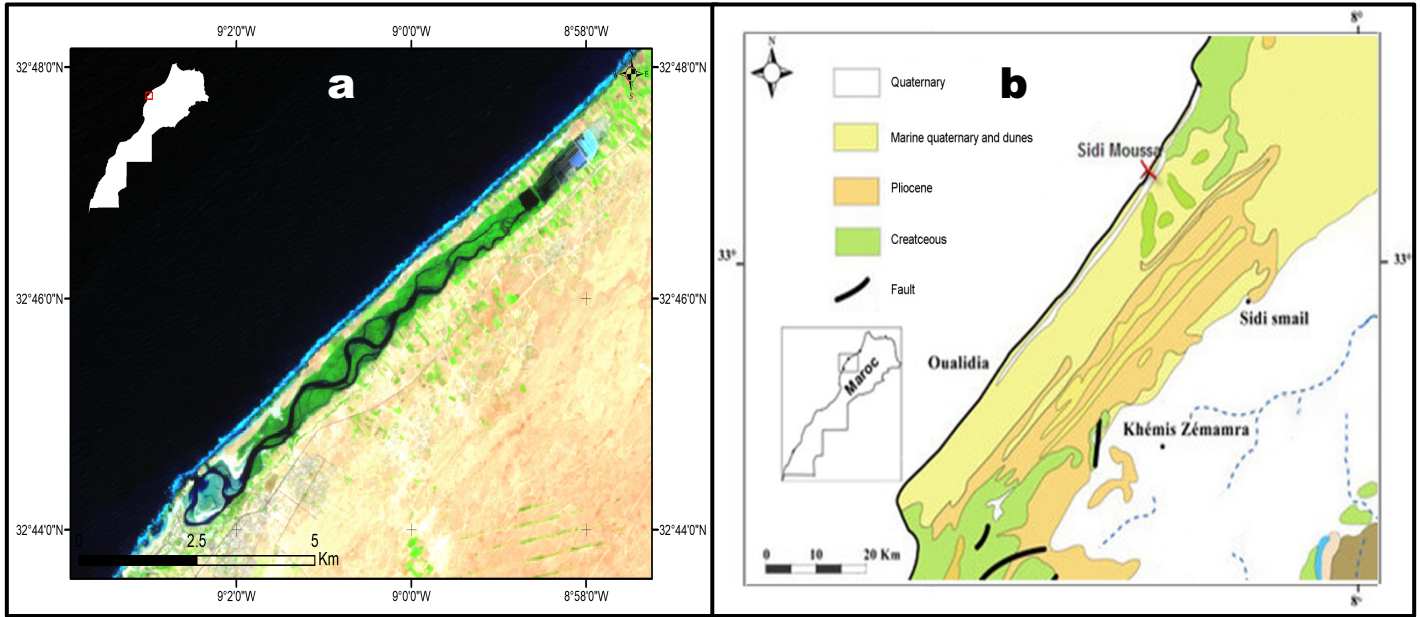


Figure 15: (a) Oualidia lagoon and (b) Geological map of Oualidia region (Adapted from Daghor *et al.*, 2016).

The lagoon morphology is characterized by adjacent streams, associated with a meandering mainstream, with an average depth of 2m and a maximum depth during flood tides not exceeding 5m. The average annual rainfall is 380 mm (Maanan, 2008) and the average water temperature is 19.1 °C (Montaudouin *et al.*, 2016). It has a groundwater input (Abdelhak, 2014). This lagoon and the surrounding region are part of a vast natural coastal area called "sahel" which belongs to the large structural unit, the Western Moroccan Meseta. It is marked by a low sandy depression geomorphologically, that is limited by a Plio-quaternary cliff (Fig.15b) and forming a large consolidated sand dune barrier separating the coast from the Atlantic ocean (Fadili *et al.*, 2016a, 2017). These dunes are SSW-NNE oriented with a range of altitudes between 100 and 150m (Fadili *et al.*, 2016b).

I.3. Nador lagoon:

The Nador lagoon (or called Mar Chica) is the largest one in the country. Located in the North of Morocco. It occupies an area of 115 km² (Fig.16a) including the cities of Nador in the centre,

Beni Ansar in the North-East Part and Kariat Arekmane in the South-East part (García-Ayllón, 2017). It is a choked lagoon, connected to the Mediterranean Sea through an inlet of 310 m with an average water temperature of 19.95 °C. The average annual rainfall is 300 mm and the average depth is 6 m (Maanan *et al.*, 2015a).

This lagoon has freshwater input from two main rivers “Boussardour” and “Selouane” (Piazza *et al.*, 2016) and from the Bouregreg aquifer (Re *et al.*, 2014).

The lagoon is interrupted in the North by a small peninsula and has an oval shape (Raji *et al.*, 2018), with an island barrier of 25km long which was created during the upper Miocene (Louaya and Hamoumi, 2011; Hamoumi, 2012)

The geological and geomorphological characteristics (Fig.16b), the area around the lagoon consist mainly of mountain ranges sheltering a significant hydrographic drainage network, where large quantities of water comes the urban concentrations, especially during the winter season (Saddik *et al.*, 2017). Furthermore, several research identified four geological structures (Bernard-Griffiths *et al.*, 1999; Raji *et al.*, 2018), with two main NE-SW structures that are considered as active during the Neogene (Poujol *et al.*, 2014).

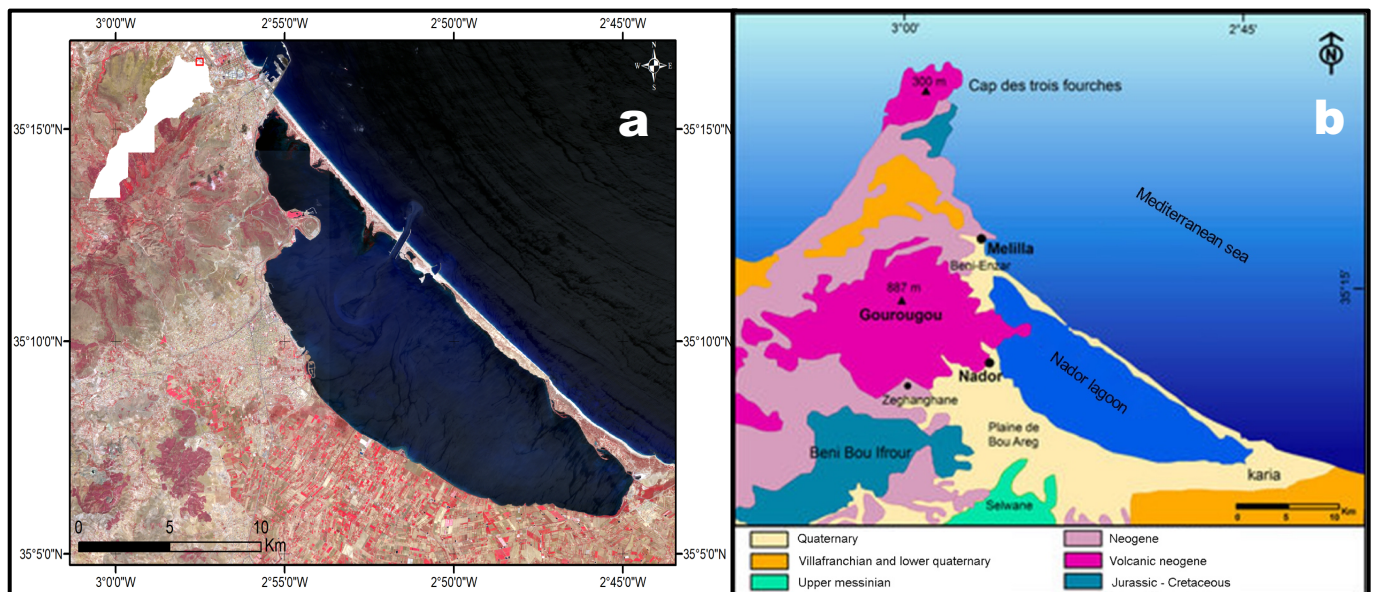


Figure 16: (a) Nador lagoon (Or Marchica) and geological map of Nador region (Adapted from Daghor *et al.*, 2016)

II. Algeria

II.1. El Mellah lagoon:

El Mellah lagoon is a geological depression which communicates with the Mediterranean Sea through one inlet (Fig.17). It is an old river valley invaded by the sea and was transformed into the lagoon (Kherifi and Bousnoubra-Kherici, 2016). It is a choked lagoon and can be classified

as a micro-tidal system with an average depth of 3.5 m (Magni *et al.*, 2015). It is located in the extreme eastern part of Algeria and 27 km from the Tunisian border. The annual average rainfall is 649 mm with an average water temperature of 20,95 °C (Benradia *et al.*, 2016). The lagoon receives freshwater from three small rivers, Mellah, Bouaroug, and R'kibet and from Bouteldja aquifer (Deraddaji *et al.*, 2015; Embarek *et al.*, 2017).

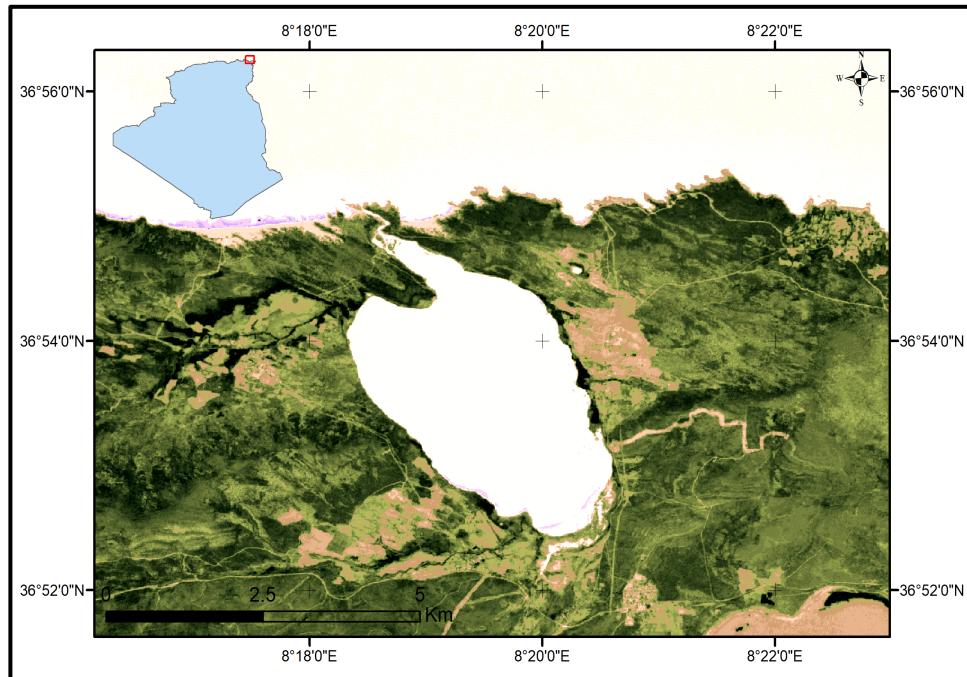


Figure 17: Location of El Mellah lagoon (Algeria)

III. Tunisia

III.1. Bizerte lagoon

The Bizerte lagoon is located on the northern coast of Tunisia in the city of Bizerte within a total area of 128 km² and an average depth of 7 m (Béjaoui *et al.*, 2017).

It is a choked lagoon connected to the Mediterranean Sea through a 6 km long inlet from the East part (Fig.18a). It has a freshwater water from many rivers and the main connection is with the Ichkeul lake through the Tinja channel from the West part, which is about 5 km long and with few meters in depth (Béjaoui *et al.*, 2017).

The average water temperature is about 19 °C and the annual average rainfall is 634 mm.

The Bizerte lagoon is considered a submerged remnant of a subsided Miocene-Pliocene basin(Fig. 18b) that is separated from the Mediterranean sea through the narrow inlet by a low rise of Tertiary limestones and sandstones (Pilkey *et al.*, 1989).

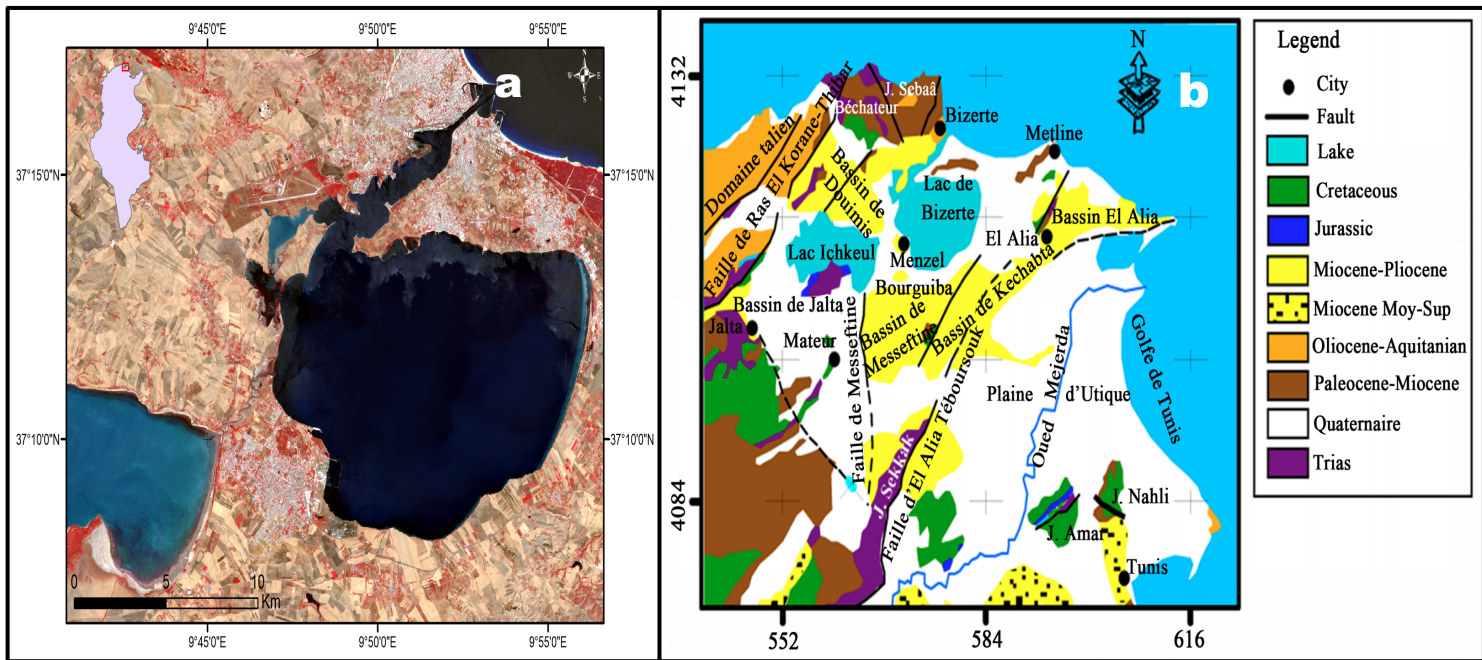


Figure 18: (a) Bizerte lagoon (Tunisia), (b) Geological map of North Eastern Tunisia (Hermi *et al.*, 2017)

III.2. Tunis lagoon

The Tunis lagoon is located in the capital of Tunisia, which called “Tunis”, the most populated city in the country. This ecosystem is divided in two part, the “Northen Tunis lagoon” and the “Southern Tunis lagoon” (Fig.16) and it is a restricted lagoon and covers an area of 29,2 km².

Tunis Southern Lagoon extends over 7,2 km² with an average depth of about 2.1 m (Fig.19). Tunis Northen lagoon is a well-mixed shallow coastal seawater covering an area about 22 km² (Fig.19a), with an average depth of 1.5 m. It is connected to the sea by only a narrow channel (about; 800 m long, 40 m wide and a mean depth of 2.5 m) (Trabelsi *et al.*, 2013). The mean annual rainfall is about 500mm and the average water temperature is 18,55 °C.

The hall lagoon ecosystem was suggested to be formed as a consequence of increased sedimentation, which probably outstanding to the Roman deforestation of the Medjerda River basin located in the northen side (Pilkey *et al.*, 1989). Structurally, this lagoon is part of a collapse that is originated during the distensive tectonic phase of Oligo-Miocene age, controlled by normal faults of NW-SE direction (Fig.19b), which played again in the ancient quaternary (Ben Ayed, 1986).

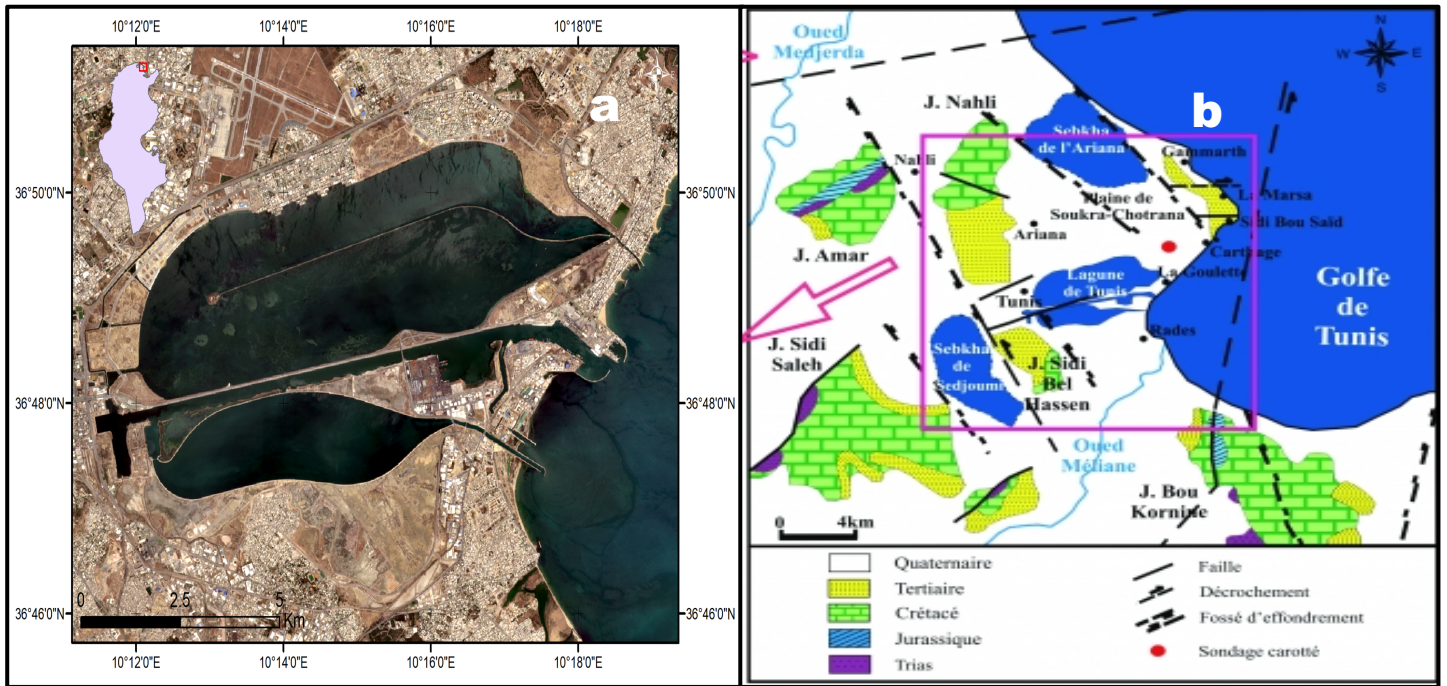


Figure 19: (a) Tunis lagoon (Tunisia), (b) Morpho-structural framework of the surrounding of Tunis lagoon (Ben Ayed, 1986).

III.3. Boughrara lagoon

The Boughrara lagoon is the largest one in Tunisia extending along the eastern south coast of the country and covering an area of 500 km² (Chalghmi, 2015).

It is a leaky lagoon connected to the sea through two direct outlets; the Ajim Jorf in the North-East with 2,33 km large and the El Kantara channel in the in the North-West with two small inlets (Fig.20a). The average depth is about 4 m, reaching a maximum of 16 m in the centre (Khedhri *et al.*, 2017). This lagoon has input from three main streams ‘El Fje’, ‘Essamar’ and ‘Bou Hamed watersheds’ streams (Khedhri *et al.*, 2017) and from Djeffara aquifer (Kharroubi *et al.*, 2012). The average water temperature is about 13°C and the mean annual rainfall is about 2010 mm.

The mainland surrounding the lagoon are characterised by various seismic fault lines that are mainly NW-SE oriented. Furthermore, three main types of terrain could be distinguished, the cliffs, the coastal mountain range and deltas, and a basin with an elongation shape (Khedhri *et al.*, 2016).

The geological settings consist of alternating continental and marine origin deposits (Fig.20b). A marine, the oldest submerging layers is the superior Permian, and the most recent formations are of the recent Quaternary (Bouaziz *et al.*, 2003). The stratigraphy of the study area is marked

by the crust villafranchian that overcomes the thick Mio-Pliocene series. Villafranchian deposit consists of a limestone crust salmon , a calcareous crust or silts nodules (Bouaziz *et al.*, 2003).

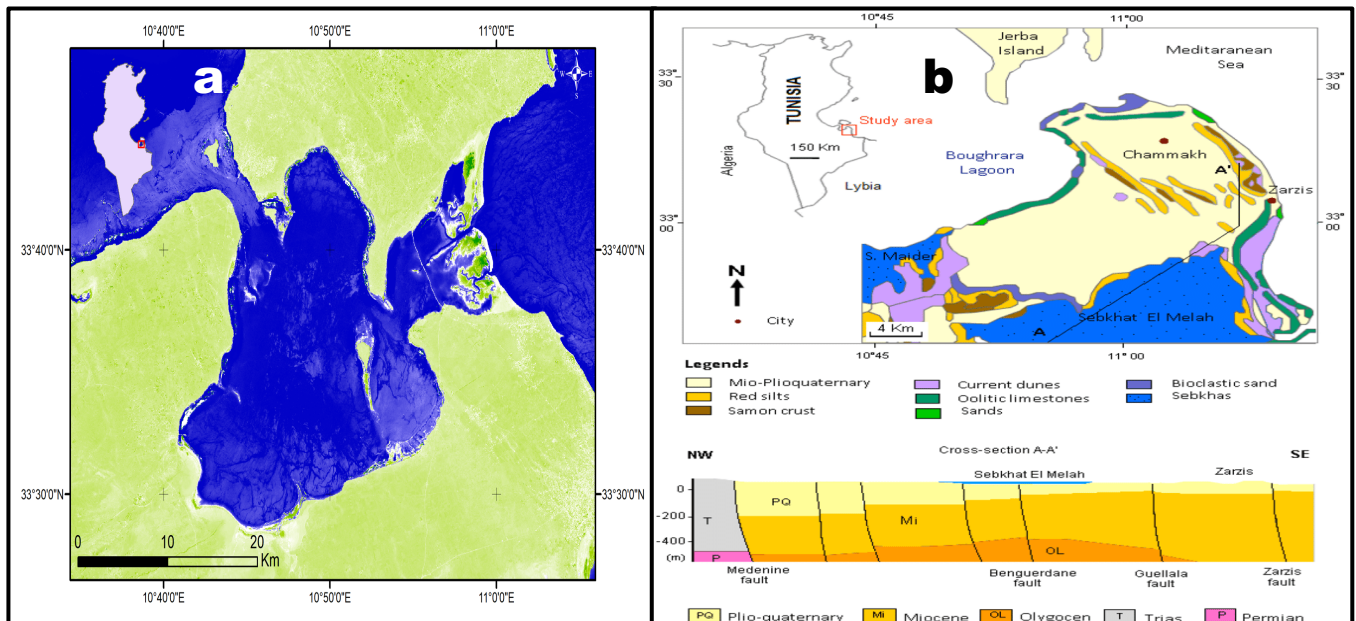


Figure 20: (a) Boughrara lagoon (Tunisia), (b) Geological map of Boughrara region (Bouaziz *et al.*, 2003)

IV. Libya

IV.1. Farwa lagoon:

Farwa lagoon (or called Farwa island) the largest one on the Libyan coast, covering an area of 32 km² (Fig.21). It is located in the Eastern part of Libya, 150 km from Tripoli its capital and 12 km from the Tunisian border and it's surrounded by the General Company of Chemical Industries (Banana and Mohamed, 2016). It is a restricted lagoon connected to the Mediterranean Sea by a large inlet in the West of 4,28 km and a small inlet in the Eastern part with a width of 0,35 km. It has no freshwater input and the mean depth is about 2 m (Ezziany-*et al.*, 2014).

The average water temperature is about 19,9 °C (Hammami *et al.*, 2013) and the annual average rainfall is about 233 mm.

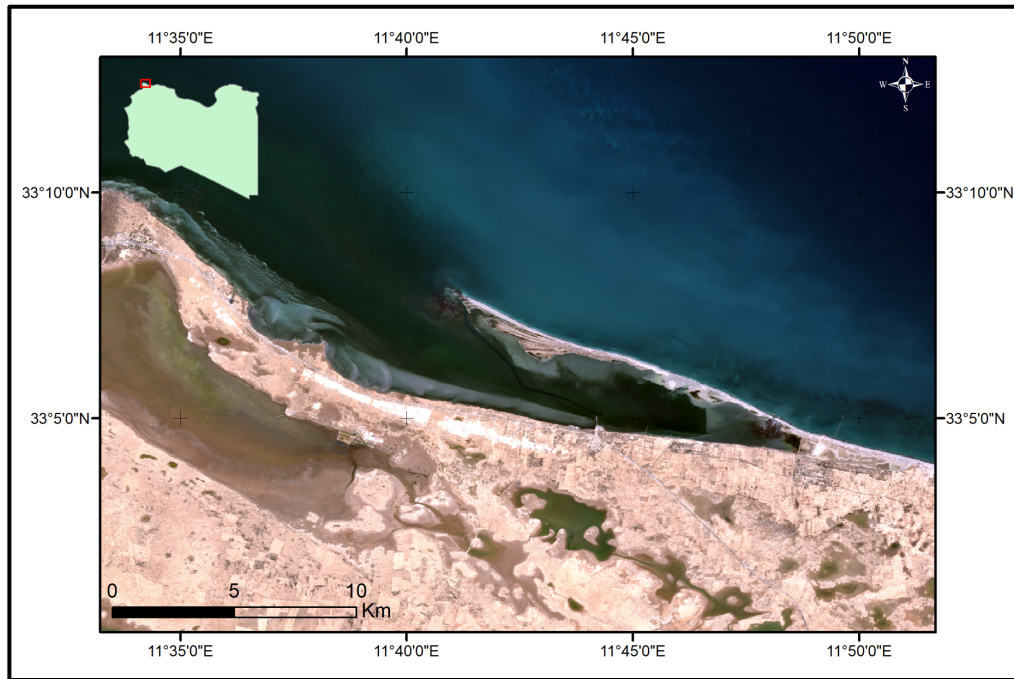


Figure 21: Farwa lagoon (Libya), Sentinel 2 image using Highlight Optimized Natural Color

V. Egypt

V.1. Marsa Matrouh lagoon

Marsa Matrouh lagoon is located in Matrouh governorate on the Western Mediterranean coastline of Egypt with a population of 447846 citizens and around a million visitors during summer time (Mulazzani *et al.*, 2017).

It is a choked lagoon, opened to the sea by an inlet of 1,5 km large (Fig.22) with a series of rocks forming a natural breakwater that allows some wave penetration (Abdel Ghani, 2015). It covers an area of 26 km² and its beaches extend for a distance of 7 km, the most important are the El Gharam and the Rommel beaches. It has an average depth of 2 m (Fenton, 2013) and it has no freshwater input. The average water temperature is about 24,75 °C (Gharib *et al.*, 2011a) and the mean annual rainfall is around 137,5 mm.

Several previous geomorphological researches that were conducted on the region surrounding the Marsa Matruh lagoon and region showed an extended calcareous ridge that originated from the continental, the marine, and the marine/environmental conditions (Torab and Dalal, 2015).

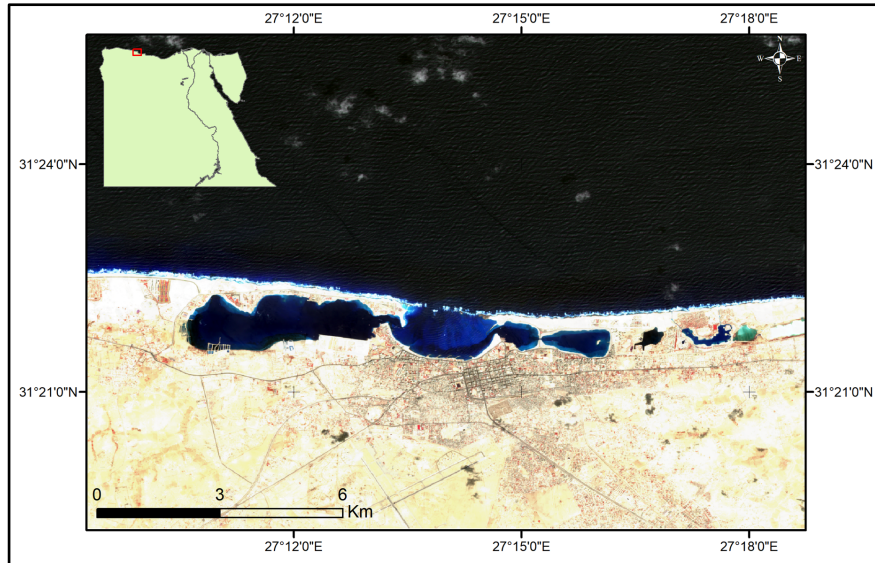


Figure 22: Marsa Matrouh lagoon (Egypt).

V.2. Burullus lagoon

The Burullus lagoon (Called Lake Burullus in Egypt) is one of the largest lagoons in the country and it is a part of the Deltaic Mediterranean coast known by Nile Delta and located in Kafr El-Sheikh Governorate (El-Amier *et al.*, 2017). This lagoon is the most impact ecosystem by pollution in Egypt. It is a choked lagoon connected to the Mediterranean Sea by a small inlet of 180 m and has an average depth of 2 m (Orabi *et al.*, 2017) and it covers an area of 460 km² with a freshwater input from the eastern side of the Rosetta branch of the Nile river (Fig. 23a). The mean annual rainfall is 200 mm and the average water temperature is about 19,5 °C (Orabi *et al.*, 2017). The lagoon consists of 46 km long and 6 km wide sandy dune barrier, that is separating this ecosystem from the Mediterranean sea, which is mostly considered as a backshore plain with low dunes (Arbouille and Stanley, 1991). Furthermore, the eastern side is characterised by a low-relief beach accretion ridges, mainly WNW-ESE oriented that are enclosed by a series of linear depressions (Arbouille and Stanley, 1991).

The resulted geologic map (Fig 23b) indicates that all rock types forming this region are from quaternary age (El-Hattab, 2015). Large areas of the region are composite of Nile silt especially along western parts of Rosetta promontory. Sands forming sand dunes are the common rock type in the eastern part of Nile Delta and Abu Qir Bay. Sabkha deposits and marsh, silt, clay evaporates are characterizing the central parts of AbuQir Bay and Eastern parts

of Delta. Sands, gravels and recent coastal deposits are found along the Delta between the two branches of River Nile (El-Hattab, 2015).

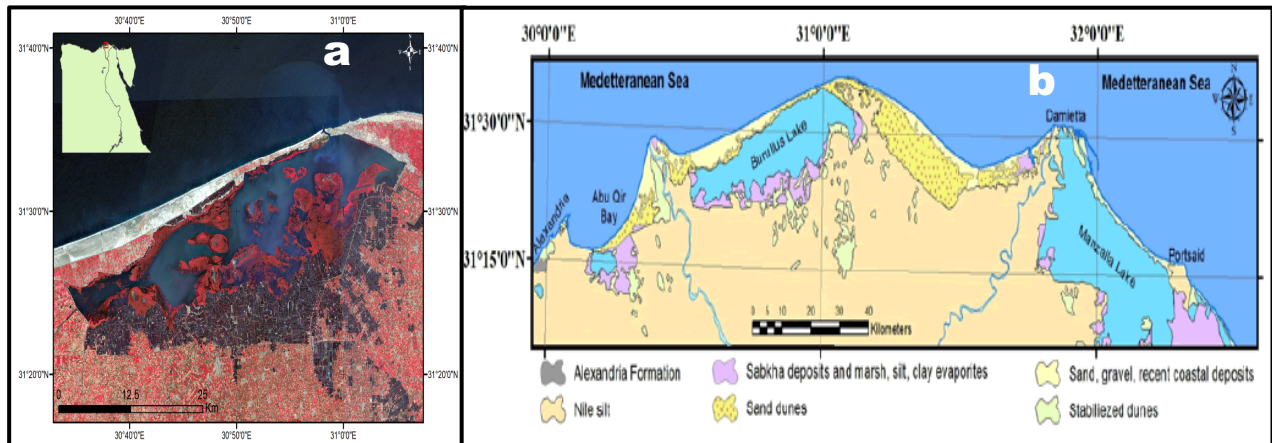


Figure 23: (a) Burullus lagoon (Egypt), (b) Geological map indicating rock type (El-Hattab, 2015)

V.3. Bardawil lagoon

The Bardawil lagoon is the largest one in Egypt, it is located in the northern side of Sinai Peninsula, 40 km from the East of Port Said and 20 km from the West of El Arish city. It covers an area of 685 km² and extends for a Width of 80 km and a length of 20 km (Abomohra *et al.*, 2017; Nassar *et al.*, 2018). It is a leaky lagoon with many inlets and it is delimited from the south by a sand dune belt and from the north by a curved sand barrier (Fig.24) that splits it from the Sinai Mediterranean coast (Abomohra *et al.*, 2017).

The lagoon has an average depth of 1,21 m (Abd Ellah and Hussein, 2009) and has a freshwater from the Quaternary aquifer of the region which contributes by 1,7% of the total inflow to the system (Ramadan *et al.*, 2014). It has an average water temperature of 20,5 °C (Abdel Razek *et al.*, 2016) and the mean annual rainfall is about 90 mm (Abomohra *et al.*, 2017).

Two main basins are characterising the lagoon, the eastern and the western basins. The first one represents a large barrier that separates the lagoon from the Mediterranean sea, known as the “Bardawil barrier”, while the second one represents small barriers that were developed within the lagoon and known as the “lake barriers” or “lagoons barrier”(Embabi and Moawad, 2014). (Embabi and Moawad, 2014) suggested that Bardawil basins are of tectonic origin due to their sediments thickness, depth of the basin and the local tectonic lineaments.

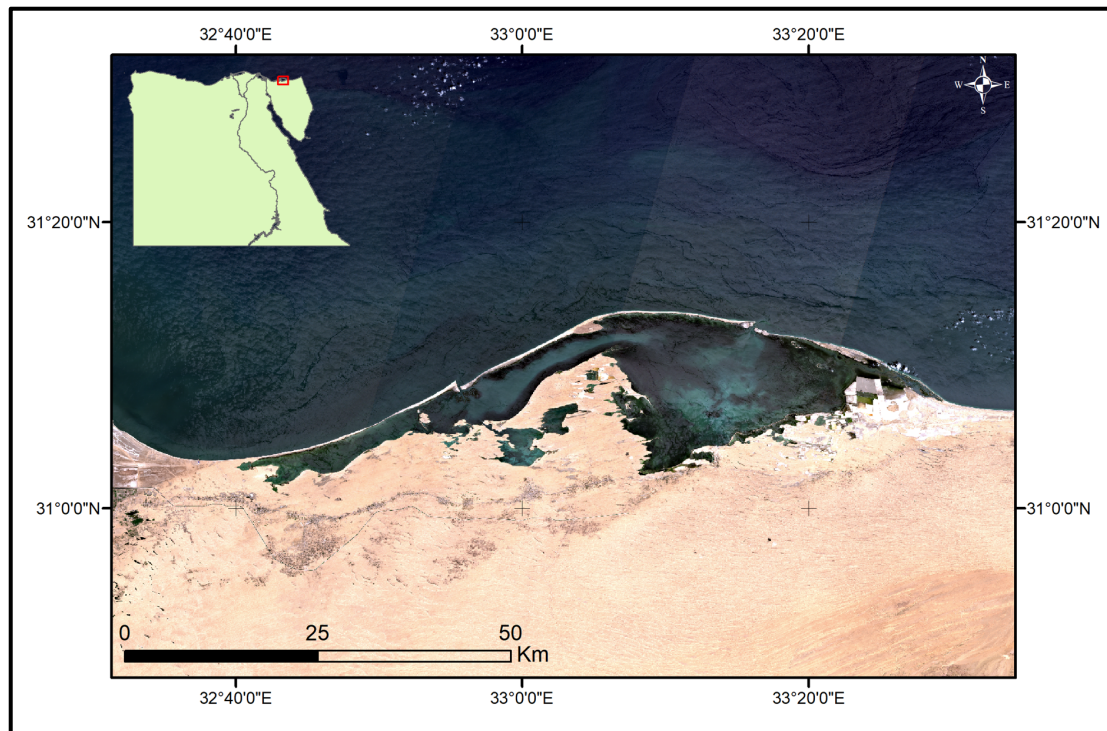


Figure 24: Bardawil lagoon (Egypt

CHAPTER 2: MATERIALS AND METHODS

I. Materials

I.1. Materials used for analysing North African coastal lagoons

The data used for analysing North African coastal lagoons were found in web-based searches using Web of Knowledge (ISI Web of Science), Science Direct (Scopus), Google Scholar and Google Searches. Searches were constrained to the period from 2000 - 2018 to focus on the most recent publications (531 articles). This identified peer reviewed articles in ISI journals (e.g. 89 for Nador), as well as a significant body of ‘grey’ literature (106 reports) such as reports by Environmental agencies or Ministries (e.g. 15 for Nador). There was considerable variation in the number of sources available for the different systems (e.g. 104 for Nador, only 24 for Khenifiss).

The search words were applied in English, French, and Arabic. Most of the articles listed in Reference section are from peer reviewed literature in English and French, published for an international audience. There is also a substantial literature in Arabic and French, which is used in the North African countries for reports, that was consulted for this review, but this is not in the reference section.

The search keywords that were used, both singly and in combination were: “name” of the lagoon, including local variations on their names; “lagoon, lake, lac, lagune,”; “country”, also in the different languages”. The studies identified were selected in a systematic manner based on title and abstract eligibility according to keywords, then the full-texts were screened. Many studies were removed due to missing data (313 articles and reports).

We then extracted information about the lagoons in relation to the drivers, activities, pressures, state changes, impacts, humans, and welfare issues as identified by Elliott et al., 2017 (e.g. agriculture, pH change, underwater noise). The reported presence or absence of various activities/pressures/state changes/impact (on welfare) in the studied lagoons were extracted and tabulated, with some quantitative and qualitative details mentioned in each result section, if data were available (e.g. number of catches, number of boats, input of pollutants).

I.2. Remote sensing technologies for environmental assessment

The new Millennium era of data collection through earth observation technologies and sensors (Fig.25) is becoming more widely used for monitoring sectors related to the coastal and marine environment (Melesse *et al.*, 2007; Unninayar and Olsen, 2015; Sanders and Masri, 2016; Asa

Strong and Elliott, 2017; Bean *et al.*, 2017; Guo *et al.*, 2017; Vihervaara *et al.*, 2017; Murray *et al.*, 2018; Voulvoulis and Burgman, 2019; Fingas, 2019a; Le Traon *et al.*, 2019) . As these data are collected routinely, they could provide a basis for synoptic-scale analysis covering a larger area over a time series. Furthermore, these datasets are sometimes open-source and easily accessible, especially when data acquisition is realized by government bodies and institutions, providing a large volume of freely accessible data for analysis and dissemination.

Traditional techniques of point sampling and observation in the environment do deliver high information content (Asa Strong and Elliott, 2017), but they are expensive and often do not provide adequate spatial and temporal coverage, while remote sensing can provide cost-effective solutions, as well as data for locations where there is no or only limited information (Cristina *et al.*, 2015).

Six remote data collecting technologies could be identified for improving integrated coastal and marine environmental management based on DAPSI(W)R(M). An updated version of the widely used Driver–Pressure–State–Impact–Response framework (DPSIR) (Gari, Newton and Icely, 2015b), such as Remote Sensing (SRS), Aerial Remote Sensing (ARS), Unmanned Aerial Vehicle (UAV), Unmanned Surface Vehicles (USV), Unmanned Underwater Vehicles (UUV), and Static Sensors as Ground Methods (SS).

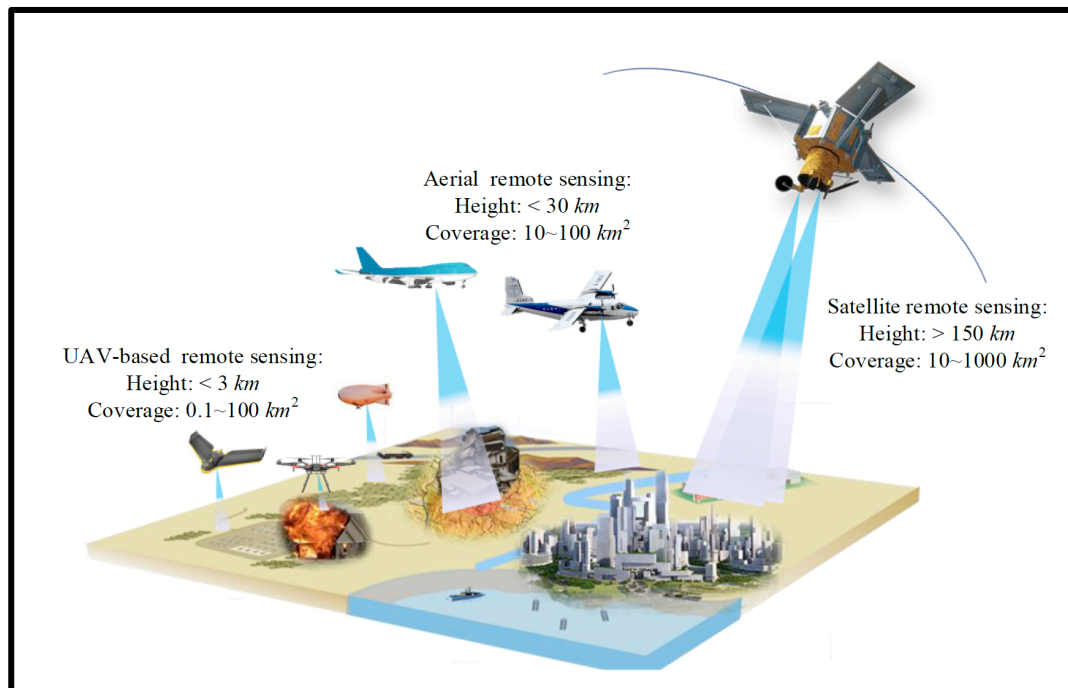


Figure 25: Types of some remote sensing platforms and their coverage areas (Xiang *et al.*, 2019).

II. Methods

II.1. Integrated system approach for managing environments

Coastal or marine environments are complex systems of interactions between morphological and physical structures, continuously varying physicochemical processes and varying ecological structure and functioning.

For managing these environments; including lagoons as Socio-Ecological System (SES), conceptual models are required to organise, visualize, understand and clarify the issues concerning an actual or predicted conditions and in what way they might be explained and solved. They can be considered as representing an organisational schemas, which recapitulate information in a standard, logical and hierarchical method (Patrício *et al.*, 2016).

Many frameworks have been developed for this purpose, such as, Systems Approach Framework (SAF), a general framework for analysing the sustainability of social-ecological systems (called OSTROM framework) and The Drivers-Pressures-State-Impact-Responses (DPSIR that became DAPSI(W)R(M)).

II.1.1. Systems Approach Framework

The Systems Approach Framework (SAF) is a protocol adopted by the Science and Policy Integration for Coastal Systems Assessment project (SPICOSA, 2009). It can be used to investigate the dynamics of coastal zone systems (such as lagoons) and potential consequences of alternative policy scenarios (SPICOSA, 2009). Moreover, the framework includes the socio-ecological and economic components of coastal areas.

The application of the SAF works across four steps and produces outputs that can be communicated to stakeholders and policy makers correspondingly. It helps also to create a permanent dialogue between scientists and stakeholders.

First step is the ***System design*** which contains five sub-tasks. These are issue resolution, system definition, conceptual model development, methods and information requirements and problem scaling.

Second step is the ***System formulation*** which provide conceptual, mathematical and numerical models by simulating system behaviour or its ecological, economic and social components.

Third step is ***System appraisal*** that involves the construction of a simulation model that incorporates the Ecological-Social-Economic (ESE) components and simulating scenarios

resulting from management responses. The results of the simulations, then, are documented and interpretatively analysed

Final step is **System output** which involves the preparation of the output package and dissemination in appropriate formats to stakeholders, including policy makers. It provides a particularly useful platform for a stakeholders' forum to execute three important tasks of recapitulation, presenting scenarios and conducting deliberations.

The SAF has been designed, developed and tested by 54 research institutes and universities across the European Union. For lagoon application, (Gari *et al.*, 2010) defined eutrophication management options in the Ria Formosa lagoon by using the SAF.

II.1.2. OSTROM Framework

The framework was proposed for application to a relatively well-defined domain of common-pool resource management situations in which resource users extract resource units from a resource system (Ostrom, 2009). The aim is to analyse the sustainability of Social-Ecological Systems (SES) that integrated the works of many scholars over years to develop an integrative and multidisciplinary methodology to understand complicated interactions within diverse systems and scales around natural resources governance (Epstein *et al.*, 2013).

The framework has 8 first-level core sub-systems describing the **interactions** (I) between four multi-linked subsystems; **resource units** (RU), **resource system** (RS), **governance system** (GS) and **users** (U) that produce **outcomes** (O) and interacts with the social, economic and political **settings** (S) and with the related **ecosystems** (ECO). (Ostrom, 2009) advised a set of 53 second-level variables to integrate the principal characters of each subsystem, but left open the possibility to select other second-level variables or add a profounder level of variables regarding the particularities of the studied SES.

This framework has attracted great attention around the world, it has been broadly used to analyse small scale and large-scale SES (Delgado-serrano, 2015; Gari *et al.*, 2017).

II.1.3. DAPSI(W)R(M) Framework

- **Emergence of “PSR” to “DPSIR” to “DAPSI(W)R(M)”**

Since the early 1990s, the Pressure-State-Response (PSR) frameworks have dominated to conceptualizing marine ecosystem risk analysis and risk management issues and later translating those for stakeholders, environmental managers and researchers (Patrício *et al.*, 2016). The PSR model (Fig.26) has initially been proposed by (Rapport and Friend, 1979) and

then developed and promoted by the OECD-Organization for Economic Cooperation and Development concept to organise its work on environmental policies and reporting using a core set of chosen indicators (OECD, 1994). The framework aimed to link anthropogenic Pressures with State changes and Impacts (Fig.26) and it has the advantage of being one of the simplest frameworks to understand and use (Linster, 2003).

It has been used within an environmental context (EEA, 1995; Turner *et al.*, 1998; Liang, Liming and Guijie, 2010; Hua, Yan and Limin, 2011; Zhou *et al.*, 2013).

In the 1995, PSR model was converted to DPSIR (Drivers-Pressures-State-Impact-Responses) approach. It was established by the European Environment Agency (EEA) programme and used in Dobris assessment of the European environment (EEA, 1995).

Numerous international organisations, contributed also to the development and the application of the framework to the environment, such as: US Environmental Protection Agency (EPA, 1994), United Nations Environment programme (UNEP, 1994), European Union through the DITTY project, LOICZ-Land ocean interactions in the Coastal Zone and the EEA (Gari *et al.*, 2015a). They noted that this was the best suitable approach to structure environmental information.

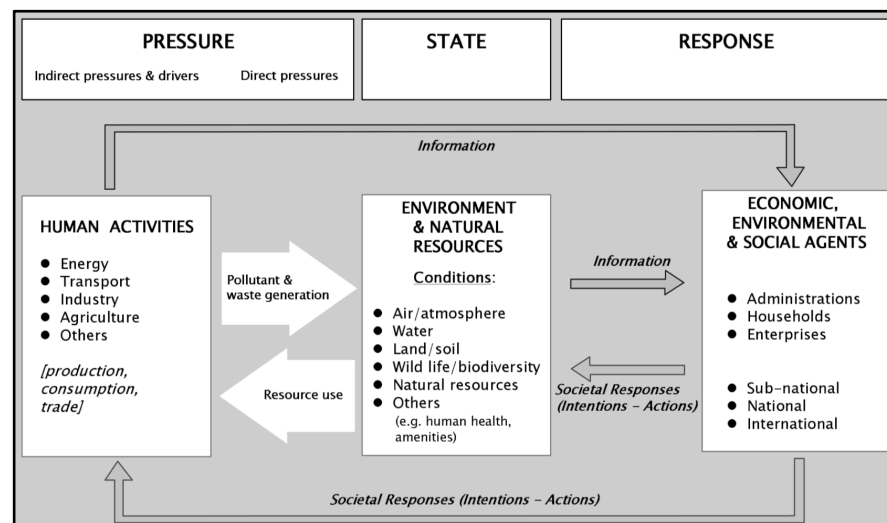


Figure 26 : Schema of the PSR framework (Linster, 2003).

The DPSIR approach was an accepted, valuable and holistic problem-structuring framework which can be used to evaluate the causes as pressures, conditions, scenarios and pertinent responses to change (Atkins *et al.*, 2011; Patrício *et al.*, 2016). It has been used widely in the literature (Fig.27) as a tool associating natural science and management of human uses, especially in Europe and applied to the issues of marine environments (Patrício *et al.*, 2016).

In latest years, there has been countless modifications to the terminology of the framework (Fig.28) and it was one of the reasons that has contributed to differences in the application of DPSIR (Gari *et al.*, 2015; Patrício *et al.*, 2016). State was considered to be “state change” and Impact as “impact on human system” (Elliott *et al.*, 2006) and on human welfare.

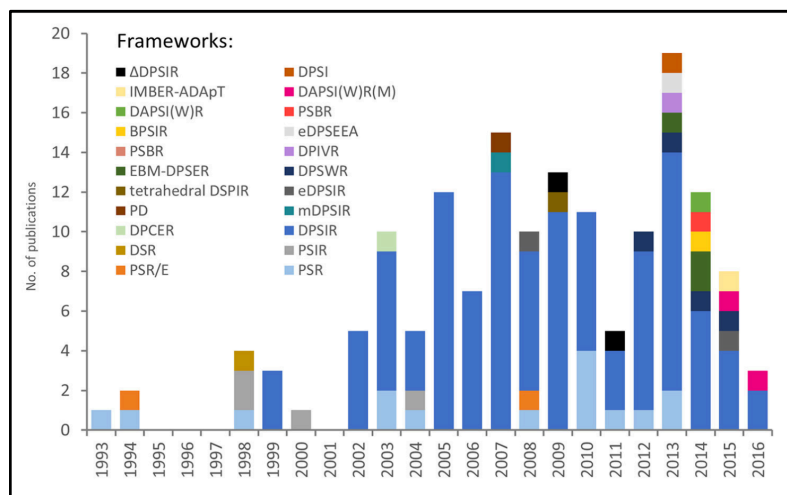


Figure 27: Studies published per year using the DPSIR framework and its derivatives, $N=152$ (Patrício *et al.*, 2016).

The most used nomenclature was DPSIR framework as an integrated “system approach” (Newton *et al.*, 2012). Although these framework were continuously evolving; in the area of human health, DPSIR has been used as DPSEEA framework (Fig.28,29) comprising Driving Forces-Pressures-State-Exposure-Effect-Action (and sometimes DPSEEAC, where “C” relates to Context), an approach used principally in risk assessments for contaminants and developed by the WHO-World Health Organization (von Schirnding, 2002).

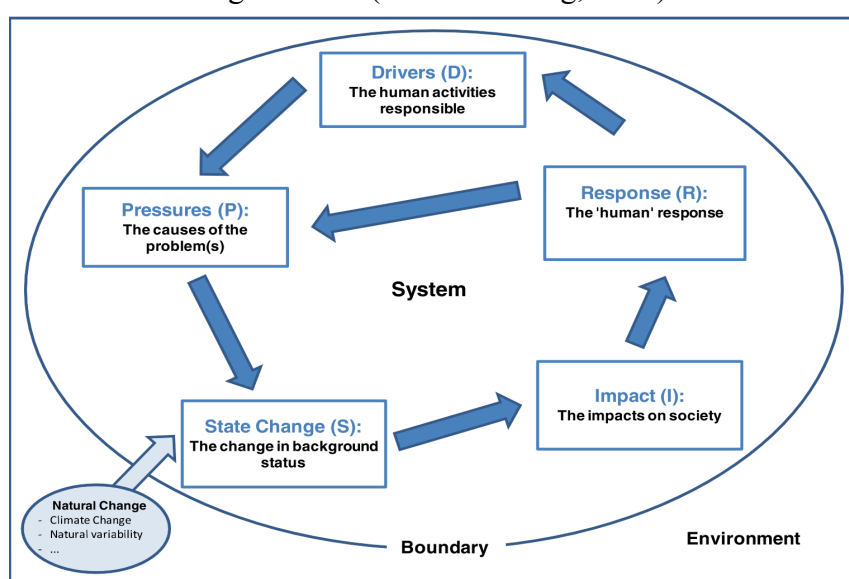


Figure 28 : The DPSIR framework as a cycle and system in the environment (Atkins *et al.*, 2011).

Driving forces signify the basic human needs such as food, space, protection, energy, transport and goods. For this reason, society carries out socio-economic Activities such as fishing, aquaculture, farming, building infrastructures and extraction of natural resources which have numerous effects and lead to Pressures that could be in local and global scale linked to climate change, either positive or negative. These effects indicated the State change on the environments (physico-chemical and ecological system). In turn, these lead to Impacts (on human Welfare including Wellbeing) such as ecosystem services, fish stocks, clean water for recreation. Those then require very different management appropriate policies Responses (as Measures) to changes resulting from Drivers, Activities and Pressures (Fig.30), which that may be brought about by-passing laws, producing regulatory forms, using economic mechanisms and technologies (Wolanski and Elliott, 2015; Elliott *et al.*, 2017).

Additionally, the complexity of any managed coastal or marine area in terms of various activities requires to links all components of DAPSI(W)R(M) framework and then to find out the connectivity between marine ecosystems and its catchment.

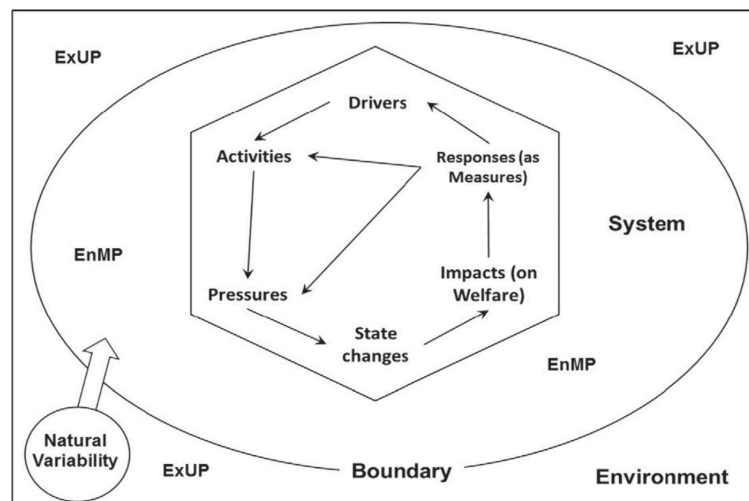


Figure 30 : The DAPSI(W)R(M) problem structuring framework. Key: ExUP=Exogenic Unmanaged Pressures; EnMP=Endogenic Managed Pressures (Elliott *et al.*, 2017).

Each section of DAPSI(W)R(M) framework is further explained below:

- **Drivers:** indicates firstly, the basics of human needs linking to an individual's survival and comprise both physiological necessities (e.g. food, air, drinking water) and security (e.g. protection from storms and risks) in order to preserve physiological needs of society (Elliott *et al.*, 2017). These forcing drivers can also include Aesthetic needs (e.g. beauty, stability, form, etc.). The aim is to find out equilibrium between both economic welfare and physiological and psychological well-being.

- **Activities:** reflect the multiple socio-economical human activities. In the context of lagoons, they can be grouped into many sectors, each of which then encompasses many activities (Tab.3). For example, within the coastal infrastructure sector there are many types of activities (Artificial reefs and bridge building “e.g. Tunis lagoon”, communication infrastructure (cables), culverting lagoons (Tab.3).

Human activities in lagoons are sources of changes in population growth, urbanisation, land-use, as well as industrial progress and transport that disturb the structure and function of these vulnerable and valuable coastal ecosystems (Newton *et al.*, 2014).

In recent years, there is an increasing exploitation of the Blue Economy such as marine energy extraction, aquaculture, blue biotechnology.

Table 3: Main activities in the coastal lagoons ecosystems (Elliott *et al.*, 2017).

Sector	Example of Activities in coastal lagoons
Aquaculture	Culture of fin-fish, macro-algae, predator control, shellfisheries
Extraction of living resources	Benthic trawling (e.g. scallop dredging), discharging fishery wastes, netting (e.g. fixed nets), potting/creeling, suction(hydraulic) dredging, bait digging, seaweed and saltmarsh vegetation harvesting, bird egg and shellfish hand collecting, curio collecting
Transport and shipping	Ejecting litter and debris, mooring/beaching/launching, shipping, producing shipping wastes, operating ferries
Renewable energy	Building and operating for devices for renewable (tide/wave/wind) power generation
Non-renewable (fossil fuel) energy	Building and operating oil and gas installations, power stations, discharging thermal wastes (cooling water), marine fracking
Non-renewable (nuclear) energy	Nuclear effluent discharge, nuclear power construction and operation, thermal discharge (cooling water)
Extraction of non-living resources	Water abstraction and operating desalination plants, mining for inorganic and particulate materials, non-living maerl, rock/minerals
	extraction by coastal quarrying, sand/gravel (aggregates) extraction, water for salt extraction
Navigational dredging	Capital and maintenance dredging, removal of substratum, dredged material disposal
Coastal infrastructure	Artificial reefs and barrage building, beach replenishment, communication infrastructure (cables); culverting lagoons, building dock/port facilities, groynes, land claim, marinas, pipelines; removal of space and substrata, constructing sea walls/breakwaters, urban dwellings, i.e. housing and other, buildings.
Land-based industry	Industrial effluent treatment and discharge, industrial/urban emissions (air), discharging particulate waste, desalination effluent, sewage
	and thermal discharge
Agriculture	Agricultural waste production, coastal farming, coastal forestry, operating land/waterfront drainage
Tourism/recreation	Angling, boating/yachting, diving/dive site operation, litter and debris production, public beach use, tourist resort and water sports operation
Military	Disposal areas operation, infrastructure building, munitions testing and use; warfare
Research and education	Animal sanctuaries, marine and coastal research; engaging in field education and training
Carbon capture and storage	Exploration, construction, operation of carbon capture and storage

- **Pressures:** Given the central position of lagoon in the connectivity between the land and the sea, they are directly or indirectly exposed to multiple pressures related to one or more human activities (local scale) (Wolanski and Elliott, 2015) and also to climate change (global scale).

Elliott *et al.*, (2017b) separated spatially these pressures into both Exogenic Unmanaged Pressures (ExUP) and Endogenic Managed Pressures (EnMP) on the system. The (ExUP) are the consequences of climate change coming outside the lagoon area and its catchment and whose reasons cannot be managed (Tab.4). There are many examples of the (ExUP) such as Thermal regime change, pH changes, water flow rate change, etc.

Table 4: Examples of Exogenic Unmanaged Pressures (ExUP).

Pressure	Description
Thermal regime change	Temperature change (average, range, variability) due to climate change (large scale)
Salinity regime change	Salinity and freshwater run-off change (average, range, variability) due to climate change (large scale)
Emergence regime change	Change in natural sea level (mean, variation, range) due to climate change (large scale) and isostatic rebound
Water flow rate change	Change in currents (speed, direction, variability) due to climate change (large scale)
pH changes	Change in pH (mean, variation, range) due to climate change
Change in wave exposure	(large scale), volcanic activity (local) Change in size, number, distribution and/or periodicity of waves along a coast due to climate change (large scale)

The Endogenic Managed Pressures (EnMP) on the system are exerted from diverse human activities and they are appearing inside the management area boundary (Elliott *et al.*, 2017). Their sources and effects need treatment and which can be managed, for example; domestic effluents from untreated sewage of the residents and seasonal variability of population that contributes to high nutrient inputs, use of the fertilisers (Nitrogen and Phosphor) in the agriculture and inputs of contaminants, such as pesticides and herbicides (Tab.5).

To manage endogenic pressures, it is indispensable to define all the effects, often named the ‘footprint’ of the pressures, both singly and cumulatively, over both space and time (Elliott *et al.*, 2017). lagoons have the particularity of being subject to strong (EnMP) around the world (El-Asmar *et al.*, 2013; Newton *et al.*, 2014; Chouari, 2015a; Giuliani *et al.*, 2015a).

These pressures reflect the mechanisms of change and can result in changes to the natural system (State changes) and subsequently the social system (Impacts on human Welfare).

Table 5 : Examples of Endogenic Managed Pressures (EnMP) (Smith et al., 2016).

Pressure	Description
Smothering	By man-made structures/disposal at lagoon
Substratum loss	Sealing by permanent construction (coastal defenses/wind turbines), change in substratum due to loss of key physical/biological features, replacement of natural substratum by another type (e.g. sand/gravel to mud)
Changes in siltation	Change in concentration of suspended solids in the water column (dredging/run-off)
Abrasion	Physical interaction of human activities with the seafloor/seabed flora and fauna causing physical damage (e.g. trawling)
Selective extraction of non-living resources	Aggregate extraction/removal of surface substrata
Underwater noise	Shipping/acoustic surveys
Litter	Waste products disposed of inappropriately into lagoons
Thermal regime change	Temperature change (average, range, variability) due to thermal discharge (local)
Salinity regime change	Temperature change (average, range, variability) due to thermal constructions affecting water flow (local)
Introduction of synthetics compounds	Pesticides, anti-foulants, pharmaceuticals
Introduction of non-synthetic compounds	Heavy metals, hydrocarbons
Introduction of radionuclides	Radionuclides
Introduction of other substances	Solids, liquids or gases not classed as synthetic/non-synthetic compounds or radionuclides
Nitrogen and phosphorus enrichment	Input of nitrogen and phosphorus (e.g. fertiliser, sewage)
Input of organic matter	Input of organic matter (industrial/sewage effluent, agricultural runoff, aquaculture, discards etc.)
Introduction of microbial pathogens	Introduction of microbial pathogens
Introduction of non-indigenous species and translocations	Through fishing activity/netting/aquaculture/shipping
Selective extraction of species	Removal and mortality of target (e.g. fishing) and non-target (e.g. by catch, cooling water intake) species
Death or injury by collision	Caused by impact with moving parts of a human activity (ships, propellers, wind turbines)
Barrier to species movement	Obstructions preventing natural movement of mobile species. bridges, causeways, wind turbines etc.
Emergence regime change	Change in natural sea level (mean, variation, range) due to man-made structures
Water flow rate changes	Change in currents (speed, direction, variability) due to man-made structures
pH changes	Change in pH (mean, variation, range) due to runoff/change in freshwater flow etc.
Electromagnetic changes	Change in the amount and/or distribution and/or periodicity of electromagnetic energy from electrical sources (e.g. underwater cables)
Change in wave exposure	Change in size, number, distribution and/or periodicity of waves along a coast due to man-made structures (local) or climate change (large scale).

- **State change:** This indicator is related to changes on the natural system due to cumulative effect of a single or multiple pressures. These are severe to the environment, particularly modifications in physico-chemical variables (i.e. dissolved oxygen, organic matter, contaminated sediments, etc.) and transformations of the health of all levels of biological organisation – the individuals, populations, communities and ecosystems (such as a lost habitat, reduced population size) (Elliott *et al.*, 2017).

Numerous ecosystem service indicators (such as aquaculture, fish stocks ...) could be functional to identify the situation of the state, comportment and trajectory of lagoon ecosystem components and processes. They are required to make the ecosystem services approach operational for lagoons managers.

The changes, if left unchecked leads to Impacts on societal Welfare.

- **Impact (on human Welfare):** represented as result from changes in the natural system (Fig.29), but which have consequences for societal livelihoods and welfare including losses of ecosystem services which ultimately produce economic benefit (such as a fish stocks, aquaculture, tourism) (Newton *et al.*, 2014). In turn, it can have loss of employment.

Another example, the loss of ‘places and seascapes’, affected by or reflecting State changes, may impact the spiritual and cultural welfare when society invest time and provide resources to obtain such benefit (Elliott *et al.*, 2017).

- **Responses (as Measures):** respond to the effects of external natural and anthropogenic influences to ensure sustainability. several pressures or activities representing risk, might require a single or integrated response as measures (Newton *et al.*, 2014; Patrício *et al.*, 2016; Elliott *et al.*, 2017). Those measures (within policy responses) include economic and legal instruments, technological devices, remediation agents, and societal desires. They can be chronic (subtle over long time periods) or acute (immediate) to address, mitigate or reduce the hazards and the risks (Patrício *et al.*, 2016).

For a successful management Responses (as Measures) to changes resulting from Drivers, Activities and Pressures (Elliott *et al.*, 2017) suggested to follow the 10-tenets approach for adaptive management and sustainability which each tenet needs its own measures (Tab.6), while one measure may cover several tenets and any one tenet requires several Measures.

As an example, Table 7 illustrates needed measures to adopt the ‘ecologically sustainable’ tenet, by making the physical, chemical and biological conditions thus restoring the natural system. In addition to these measures, others would also be required which are related to the

feasibility of technology, the viability of the economic situation based on marginal social cost and benefit comparisons, in order to successfully manage the lagoon or any marine environment (Elliott *et al.*, 2017).

Table 6: *The 10-tenets framework for examples of management responses (Elliott et al., 2017).*

Tenet	Example of measures
Ecologically sustainable	See (Tab.7)
Technologically feasible	Building treatment works, remediation habitats
Economically viable	Sufficient funding for the measure, acceptable cost-benefit analysis/ratio
Socially desirable/tolerable	Stakeholder agreement based on consultation
Legally permissible	Compliance with laws and regulations; license compliance for waste disposal
Administratively achievable	Agreement from administrative and statutory bodies such as an Environmental Protection Agency
Politically expedient	Agreement with the manifesto commitments of the ruling party
Ethically defensible (morally correct)	Funding mechanisms are not a burden on future generations, Discounting mechanisms are not a liability
Culturally inclusive	Protection of culturally and aesthetically important areas, no interference of indigenous human population areas
Effectively communicable	Agreement by consultation, advertised decision-making

The Principle of DAPSI(W)R(M) is to connect the natural and social systems, involving the natural and social sciences to deliver the socio ecological systems and system approach. this integrated approach represents a causal and cyclical pathway of risk (Elliott *et al.*, 2017) and exemplify a communication tool for allowing stakeholder interaction (Newton and Elliott, 2016). Furthermore, the approach has been adopted already in many research projects.

Cormier and Elliott (2017) analysed the recent list of indicators for the United Nations Sustainable Development goals (SDG 14) within the indicator as defined by the DAPSI(W)R(M). (Berninsone et al., 2018) developed an adaptive management plan to analyse artisanal fisheries of Pehuen Co and Monte Hermoso (Argentina) based on the results of combining the analysis-orientated Systems Approach Framework with DAPSI(W)R(M) approach.

The uses of a conceptual framework in which environmental problems affecting North African coastal lagoons, it may be assessed by the evaluation of all components of DAPSI(W)R(M) framework.

Table 7: Description of measure categories (Elliott et al., 2017)

Objective/class	Measure category
Biology/ecology/other	Measure to develop and/or protect specific habitats
	Measure to develop and/or protect specific species
Hydrology/morphology	Measure to prevent introduction of or to control/eradicate invasive species
	Measure to develop natural gradients and processes, transition and connection
	Measure for direct human benefit
	Measure to restore lateral connectivity (flooding dynamics, floodplains and off-channel habitats)
	Measure to restore water flow - quantity
	Measure to restore sediment flow - quantity
	Measure to restore water flow - dynamics
	Measure to restore morphological quality (structure and substratum)
	Measure to restore morphological diversity (depth and width variation)
	Measure to restore riparian zone
	Measure to restore tidal energy dynamics, range, asymmetry and pumping effects
	Other measures to improve morphological or hydrological conditions
Physical/chemical quality	Measure to reduce nutrient loading (point and diffuse sources)
	Measure to improve oxygen conditions
	Measure to reduce physical loading (e.g. heat input)
	Other measure to improve self-purifying power

II.2. Remote sensing technologies used for the assessment of coastal and marine environments

While DAPSI(W)R(M) is increasingly used as a holistic framework for integrated coastal and marine management (Cormier and Elliott, 2017; Burdon *et al.*, 2018; Kaikkonen *et al.*, 2018; Dale *et al.*, 2019; Lovcraft and Meek, 2019; El Mahrad *et al.*, 2020; Newton *et al.*, 2020), there has only been limited use of RS technologies to support this management framework. For instance, (Ouellette and Getinet, 2016) addressed satellite and airborne remote sensing for supporting Marine Spatial Planning (MSP) and Integrated Coastal Area Management (ICAM) by providing a list of relevant sensors. (Asa Strong and Elliott, 2017) provided guidance on remote sensing techniques that can facilitate the extrapolation process by structuring RS data effectively across multiple spatial scales in order to undertake a correct assessment for integrated marine management. (Fingas, 2019b) presented an overview of the use of optical

satellites and sensors used for ocean management and that provide a mapping of several parameters.

Remote sensing technologies have played a significant role in sensing the environment during the last five decades (Xiao *et al.*, 2019). There seem to be two different types of approaches in the literature, namely general overviews of RS technologies focusing on a single issue or a general overview of one RS technology to solve various issues. (Side and Jowitt, 2002) compared remote sensing technologies for seabed mapping by providing coverage and resolution. (Goetz, 2009) presented an overview of decades of existing hyperspectral RS for analysing the earth. (Kratzer, Therese Harvey and Philipson, 2014) developed a conceptual model to integrate ocean colour remote sensing data into coastal management with a case study in Himmerfjärden in Sweden. (Unninayar and Olsen, 2015) presented a global dimension on the use of satellites to monitor and observe the earth. (Vihervaara *et al.*, 2017) showed the role of remote sensing combined with essential biodiversity variables on improving the current state of biodiversity in Finland. (Guo *et al.*, 2017) reviewed seven types of sensors applied to wetlands, including their classification, water quality, sea-level rise, and other parameters, by presenting their advantages and limitations and providing advice on future wetland-RS research lines. (Bean *et al.*, 2017) discussed the impact of RS technologies on monitoring the whole marine ecosystem models for an integrated and comprehensive approach to impact assessments that can benefit the society in the context of a country, such as the UK. (Neukermans *et al.*, 2018) addressed critical science questions on ocean–atmosphere interaction using multiplatform space-borne missions, from visible to microwave, active, and passive sensors. (Werdell *et al.*, 2018) have presented state of the art approaches to obtain marine inherent optical properties from ocean colour RS and have defined the areas where existing knowledge gaps remain. (Murray *et al.*, 2018) suggested a framework for integrating RS data into ecosystem risk assessments and showed that unstructured use of RS data could introduce substantial error and uncertainty into this assessment.

In the present research thesis, six categories of RS technologies are considered (Fig. 31):

Satellite Remote Sensing (SRS): Land surface observations using satellite images started in the early seventies with the launching of Landsat 1. During the late seventies, the Coastal Zone Colour Scanner was launched as the first satellite intended for monitoring the Earth's oceans and water bodies by observing ocean colour and temperature, particularly in coastal zones (Krug *et al.*, 2017). Later, many other satellite sensors were developed by several space agencies and countries. (Krug *et al.*, 2017) provided a list (<https://ars.els->

cdn.com/content/image/1-s2.0-S0079661116301562-mmcl.pdf) of orbital sensors dedicated to ocean colour radiometry from 1970 to satellites proposed for the future. In general, satellite-based remote sensing images and techniques are advantageous as they usually collect uniform data with common acquisition and recording schemes, covering large areas. Furthermore, other types of sampling missions can be expensive and infrequent, which can hinder analyses that requires data with high temporal fidelity (Sanders and Masri, 2016). A full review of SRS sensors can be found in (Toth and Józków, 2016) and (Zhu *et al.*, 2018).

Aerial Remote Sensing or Manned Aircraft (ARS): This technique is known as aerial photography or airborne imagery and is based on taking photographs from a human-crewed aircraft. The first aerial photograph from a hot air balloon dates back to 1858 (Ingemar Skoog, 2010). It started in manned aircraft in 1909 and advanced, especially during world wars. For example, since the 1930s, the United States has covered most locations in the country, using photogrammetric techniques (Gorman, Morang and Larson, 1998). Manned aircraft can offer further objective and replicable outcomes with a permanent record (Niaounakis, 2017). They have succeeded in many aspects of coastal research, such as wetland assessments, beach erosion control, land-use planning, coral reefs, marine habitat, and many others (Yang and Artigas, 2009; Purkis and Klemas, 2011; Klemas, 2012).

Unmanned aerial vehicles (UAVs): Most known vehicles in this category are drones, which are unmanned aircraft that can reach difficult locations, such as wetlands. Traditionally these are used in military surveillance missions. Their use has been growing rapidly since the beginning of the 21st century with an unprecedented development for missions with high social impact (Pereira *et al.*, 2009) and for different types of environments, such as coastal areas (Klemas, 2015; Murfitt *et al.*, 2017) and marine areas (Colefax, Butcher and Kelaher, 2017; Torres *et al.*, 2018). (Papakonstantinou, Topouzelis and Pavlogeorgatos, 2016) suggested a 3D representation that can improve the classification, visualization, and mapping of coastal morphology in high resolution, using UAV images. Furthermore, (Doukari *et al.*, 2019) provided a protocol for UAV aerial survey that can improve data acquisition quality, in a timely, efficient manner that represents an effective methodology for coastal and marine survey. A full review of UAVs for photogrammetry and remote sensing is provided by (Colomina and Molina, 2014).

Unmanned Surface Vehicles (USVs): These are vehicles that operate on the water surface without a crew. They are also called autonomous surface vehicles, unmanned surface vessels, or autonomous surface crafts. Significant progress in the development of USVs occurred from

the end of the 20th century into the 21st century (Manley, 2008; Duarte *et al.*, 2016). USVs have been used for many aspects related to marine management, such as bathymetry surveys (Roberts and Sutton, 2006), sea surface sampling (Caccia *et al.*, 2005), environmental data gathering, pollutant tracking (Naeem *et al.*, 2008; Švec *et al.*, 2014), harmful algal bloom detection (Leong, Tkalic and Patrikalakis, 2012), meteorological parameters (Meyer, 2016), and even monitoring of marine fauna (Ryan *et al.*, 2010; Verfuss *et al.*, 2019). An overview of USV developments and challenges is presented by (Liu *et al.*, 2016).

Unmanned Underwater Vehicles (UUVs): These are robotic devices or vehicles that are unmanned underwater. Their deployment allows the study of many aspects of the marine environment, such as in marine geoscience (Wynn *et al.*, 2014), monitoring marine habitat (Katzschmann *et al.*, 2018; Marre *et al.*, 2019), mapping the seafloor (Thompson *et al.*, 2012), marine archaeology (Allotta *et al.*, 2015), underwater structures (Jacobi, 2015), and many other aspects. (Sahoo, Dwivedy and Robi, 2019) presented the advances in the field of UUVs.

Static Sensors (SS) as Ground Methods: These include single sensors or wireless sensor networks (WSN). They are growing in the field of environmental resource management (Sanders and Masri, 2016) and have many users for coastal and marine environments. These sensors can measure upwellings (Hu *et al.*, 2019), oil spills (Hu *et al.*, 2019), water quality, fish behaviour (Parra *et al.*, 2018), and storm detection (Barbariol *et al.*, 2019). They can also be used as biosensors for monitoring marine contaminants (Justino *et al.*, 2015) and many other applications (Venkatesan *et al.*, 2018). However, as they are typically fixed sensors, each individual sensor delivers only local observations.

Comparing these different remote sensing technologies, SRS have larger spatial coverage with large-volume time series, non-destructive sampling capabilities, and are cost-effective (McClain, 2009; Fretwell *et al.*, 2015). The launch of SENTINEL missions by the European Space Agency (ESA) under the COPERNICUS program demonstrated the importance of these technologies. They are the most ambitious earth observation (EO) systems worldwide (Jutz and Milagro-Pérez, 2018) with more than 15,000 users registered in 2019 to the Copernicus

Marine Environment Monitoring Service (CMEMS) alone, which will probably increase further after the launch of all Sentinel constellations (Le Traon *et al.*, 2019).

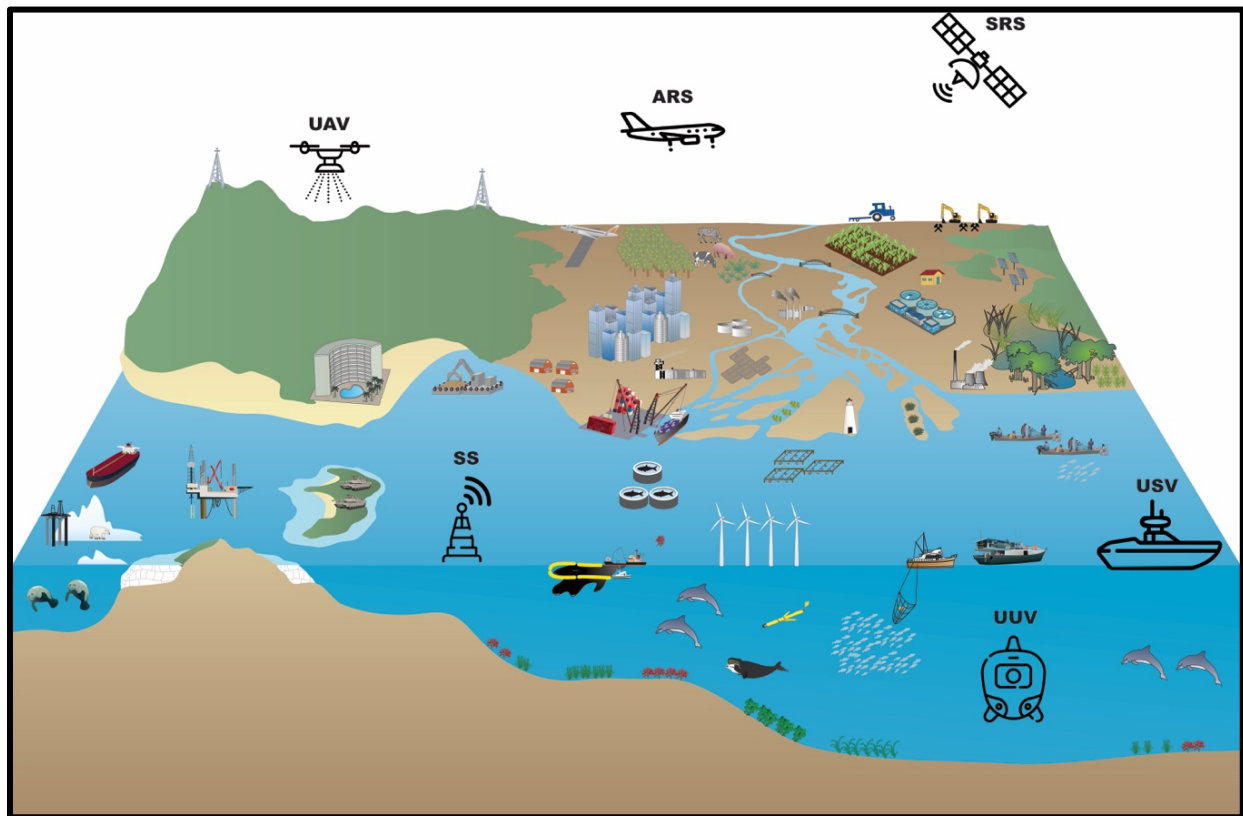


Figure 31: Conceptual diagram summarizing the main activities in coastal and marine environment and the relevant remote sensing technologies for their assessment. Symbols are courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (<https://ian.umces.edu/symbols/>). (Credit: Badr El Mahrar).

III. Conclusion

The information about North African lagoons is diffuse, heterogeneous and the terminology is often confusing. North African coastal lagoons are complex, social-ecological environments so an interdisciplinary approach is needed for their analysis and management. The DAPSI(W)R(M) approach used in the research (Elliott *et al.*, 2017) has evolved from the previous applications of DPSIR approach for lagoons analysis (Newton *et al.*, 2014; Dolbeth *et al.*, 2016).

In the following chapter, 11 out of 21 North African coastal lagoons will be analysed. Furthermore,

PART 3: ANALYSIS AND DISCUSSION

CHAPTER 1: SOCIAL-ENVIRONMENTAL ANALYSIS FOR THE MANAGEMENT OF COASTAL LAGOONS IN NORTH AFRICA: DAPSI(W)R(M) APPLICATION.

I. Drivers of changes in North African Lagoons

Societal Drivers in relation to North African lagoon context are outlined below:

Stage 1_basic biological and physiological needs: these are fundamental necessities for all humans such as food, drink, shelter etc.

Stage 2_safety needs: these include protection from inclement natural phenomena such as storms, droughts and floods; law and order; allowing for the use of goods and services from lagoons; political stability and allowing North African populations to live without fear.

Stage 3_love and belonging needs: these represent interpersonal relationships amongst North Africans; friendship, trust and acceptance, receiving and giving affection and even love. At the scale of an individual, this involves belonging to a group, having friends, creating a family. It also includes the behavior of stakeholders, (e.g. fishers, farmers, workers), citizenship and being part of society.

Stage 4_esteem needs: these are represented by an individual's achievements, self-respect, and status that are part of the common culture among North African people. For instance, men (e.g. fishers) are still the main wage earners of the household with their work providing them self-respect and the respect of others in the context of the local culture.

Stage 5_self-actualisation: the final stage is represented by realizing personal fulfilment. For example, the decision makers responsible for the Nador lagoon are trying to provide economic growth for the region based on sustainable management of the goods and services. By ensuring successful management of this type of ecosystem, they are setting not only an excellent case study for North Africa but also for the other countries in Africa and elsewhere.

II. Activities associated with North African lagoons

The assessment based on the human activities associated with North African lagoons is related mainly to general activities associated with major sectors rather than individual, specific activities. Table 8 summarizes some of the more important activities (adapted from Smith et al., 2016) occurring in these lagoons that are presented in more detail in this section. As far as possible, a common style and content has been used for the description of these activities, but there are big differences in the content and quantity of data that is presently available for the different lagoons.

Table 8: The major economic sectors and activities in North African lagoons: ‘X’ represents documented, and ‘?’ undocumented activities. List of activities adapted from Smith et al., (2016).

Country	Morocco			Algeria	Tunisia			Libya	Egypt		
Lagoon	Khenifiss	Oualidia	Nador	El Mellah	Bizerte	Tunis	Boughrara	Farwa	Marsa Matrouh	Burullus	Bardawil
Agriculture		X	X	X	X		X	?	X	X	X
Golf			X						X		
Damming of streams		X	X		X					X	
aquaculture	X	X	X	X	X	X	X	X	X	X	
Extraction of living resources	X	X	X	X	X	X	X	X	X	X	X
Tourism & recreation		X	X	?		X		X	X	X	X
Coastal infrastructures		X	X	X		X			X	X	X
Navigational dredging		X	X		?	X	X			X	X
Extraction of non-living resources		X	X					X	X		X
Land-based industry		X	X	X	X	X	X	X	X	X	X
Transport and shipping	X	X	X	X	X	X		X	X	X	X
Research and education		X	X	X	X	X	X		X	X	X
Land reclamation			?			X			X	X	X
Inlet consolidation			X		?		X		X		

II.1. Extraction of living resources and aquaculture

II.1.1. Fishing

Artisanal fisheries have been identified as common activity in all lagoons, which has increased in the last decades due to growth in local demand linked to urban growth. The fisheries activities use small fishing boats because the lagoons are shallow waters (only a few meters). The boats are called ‘feluccas’ in Morocco, Algeria and Tunisia or ‘marceb’ in Libya and Egypt.

Khenifiss lagoon (Morocco), an ecosystem protected from UNESCO World Heritage, has few fishing and aquaculture activities at present. Fisheries are more developed in Nador lagoon,

where the tonnage of the fish catches increased from 480 tons in 2001 to 1157 tons in 2012, which represents an increase of 241%. The monthly net profit per boat is around 222 Euro (2465 Moroccan Dirhams). Overall, the main fish catches are eel (i.e. *Anguilla Anguilla*), bream (i.e. *Sparus aurata*), grey and red mullet (i.e. *Mullus barbatus*). Other catches include cuttlefish, octopus (i.e. *Octopus vulgaris*), and shrimp (i.e. *Panaeus japonicus*). The 887 fishers of this lagoon are all male with an average age of 41 years (including sailors), while boat owners are of an average age of 48 years. For 46% of fishers, fishing is their only economic activity while the others work seasonally in agriculture or small commerce (Najih *et al.*, 2015).

The Mellah lagoon (Algeria) is also well-known for its artisanal fishery activities with an annual average fish production of around 40 tons. The production comprises of eels (58%), followed by mullet (31%) represented by *Mugil cephalus*, *Liza aurata*, *L. saliens*, *L. ramada* and *C. labrosus*. There is also harvesting of molluscs including clams (i.e. *Ruditapes decussatus*) and cockles (i.e. *Cerastoderma glaucum*), (Chaoui *et al.*, 2006). The only available data about fishers are from 1982, with 13 fishers supervised by “Enterprise Nationale Algérienne de Pêche- Unité Aquacole”; they are all male with an average age of 44 years, supporting a total of 67 children (FAO, 1982).

The catch from Farwa lagoon (Libya) is 26 tons annually, mainly fish, shellfish and octopus, but there is no available data about numbers of fishers (Banana and Mohamed, 2016).

Fishing production in Egypt has increased from an annual production of 140,400 tons in 1980 to 1,079,500 tons in 2009, with 934,000 tons coming from inland areas. This is an important sector for the country, representing 2 billion Euros in income. Egyptian lagoons represent 27.8% of total fisheries production in the country and are mostly for crab. (El Nahas *et al.*, 2017).

The reason for the large variation in the number of fishers and catches among North African lagoons depend on the size of the lagoon (both area and depth) as well as the population surrounding the lagoon.

II.1.2. Aquaculture

Moroccan aquaculture started in the 1950s with the launch of shellfish farming in the Oualidia lagoon, with a pilot project for breeding oysters. Currently, a dozen farms continue to operate at this lagoon. Oyster production reached 60 tons in 2011, with shell-fishing representing 15% of total production in the region (Maanan *et al.*, 2014).

Shellfish production in Tunisia started in 1964 in Bizerte lagoon (Ghribi *et al.*, 2016) and included mussels, oysters and clams (Fertouna-Bellakhal *et al.*, 2014; Turki *et al.*, 2014). Current production is over 100 tons per year.

In Libya, mussel and oyster cultivation is ongoing at aquaculture farms on Farwa lagoon.

In Egypt, fish farms have been developed along the lagoon shores of Burullus. The annual production is about 52,000 tons (Eid and Shaltout, 2014). Bardawil lagoon (Egypt) is a rich environment for the extraction of living resources. The production of high-quality fish is mainly exported to Europe, enabling an increase in economic development (El-Kassas *et al.*, 2016). This activity produces approximately 80% of the exported fish and crustacea from Egyptian lagoons (El-Kassas, Nassar and Gharib, 2016; Nassar *et al.*, 2018).

II.2. Agriculture and golf

Agricultural practices have a high impact on lagoons environments. In North Africa, many lagoons are surrounded by agriculture and, in some cases, have been modified by land reclamation, draining and infilling to enable agriculture (e.g. Burullus in Egypt). In recent years, some areas around lagoons have been converted to golf courses, although the actual locations and environmental impacts have yet to be fully analyzed.

In Morocco, an area of 92 km² surrounding the Nador lagoon is agricultural, most of which is irrigated (El Yaouti *et al.*, 2008; García-Ayllón, 2017). There is intensive cereal production to the south of the lagoon (Giuliani *et al.*, 2015b), with barley occupying 56% of total area, olive trees nearly 22% and other crops about 22% (Fig.32). Fishing activities, agriculture, and livestock production employ up to 46% of the working population in the region (Najih *et al.*, 2015).

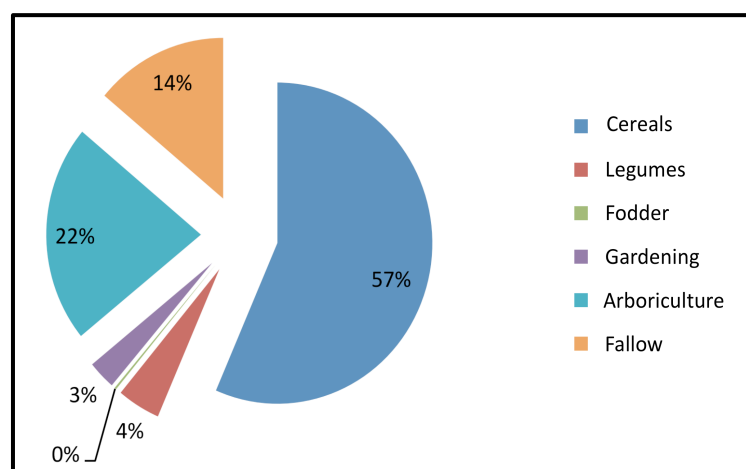


Figure 32: Distribution of useful agricultural area by crop type in the Nador region

There are intensive agricultural activities for vegetables and use of fertilizers (Maanan *et al.*, 2014) in the area surrounding Oualidia lagoon (Morocco), which have expanded in area from 10.52 % in 1946 to 40.15 % in 2006.

Only 9% of the watershed for the El Mellah lagoon (Algeria) is agricultural with an area of 7.34 km² of which 1.30 km² is dedicated to livestock, mainly cattle and goat production (Melouah, 2013).

The Bizerte lagoon (Tunisia) has a catchment area of 480 km², of which agricultural activities cover 117 km² area, with 78 km², 34 km² and 5 km² dedicated to cereal culture, horticulture and arboriculture, respectively (Garali *et al.*, 2009).

The cultivated area around Burullus lagoon (Egypt) has increased by 68.7%, from 231.31 km² in 1984 to 336,60 km² in 2015 (Husain *et al.*, 2016). This lagoon receives approximately 4 billion m³ of water per year of drainage water from a catchment area of about 403 km² of the agricultural land in the Nile Delta, (El-Amier, Elnaggar and El-Alfy, 2017; Orabi, El-Badry and Badr-ELDin, 2017).

II.3. Tourism a recreation

Lagoons ecosystems are attractive to tourism for both scenic and cultural characteristics. The most popular touristic lagoons in North Africa are Nador and Oualida in Morocco, Marina and Marsa Matrouh in Egypt.

In Morocco, the Oualidia lagoon provides many touristic activities including sailing, bathing on beaches, bird watching and nature watching (Fig.33). The seaside resort has a diversity of landscapes and in summer the population increases by 54,000 (www.hcp.ma) with a daily capacity of 30,000 people. Tourism activities have also been developed around the Nador lagoon, particularly in the northeastern part of the lagoon with new residential complexes, resorts, villas, marinas, restaurants, riads and a golf academy. This ecosystem has 20 km of coastline comprising the Boqueronisa and Arkman beaches. The new Med Marchica project aims to provide 101,200 beds and 7 marinas and to employ 80,000 people by 2020.

The Farwa lagoon in Libya is well-known for kitesurfing, which attracts tourists during the windy season, from November to March.

The Marsa Matrouh is a coastal lagoon area in Egypt where tourism is expanding. There are 10 beaches that extend for a distance of 7 km, five of them are situated in the lagoon (Abdel Ghani, 2015). In summer, up to 450,000 visitors enjoy the attractive, white, sandy beaches and

turquoise seawater (Khaled *et al.*, 2014). Because of these ecosystems services, 25 hotels have been established surrounding the lagoon and employ 7000 workers (Mulazzani *et al.*, 2017).



Figure 33: View of the Oualidia lagoon during summer time (2020)

II.4. Extraction of non-living resources and land-based industries

Many lagoons in North Africa are used for extraction of non-living resources, such as mining activities, and are also associated with industrial areas.

Nador lagoon in Morocco has several industrial activities, including mining and metallurgy such as iron, pyrite, pyrrhotite, chalcopyrite. The industrial effluent from the Selouane industrial zone is discharged into the lagoon during the wet season (Piazza *et al.*, 2016).

The Bizerte lagoon (Tunisia) has been the site of industrial development since the 1950s. There are industrial complexes of around 130 factories located in the towns of Bizerte, Zarzouna, Menzel Abderrahmn, Menzel Jemil and Menzel Bourguiba. The first and biggest was a cement factory (1950) followed by the “El Fouled” steelworks (1967). Other factories are for metallurgy, electronic industries, textile, chemical production, petrochemicals including oil refineries, agro-alimentary production, cement manufacturing, and fish processing.

The GCCI (General Company of Chemical Industries) industrial complex is located in the east part of the Farwa lagoon (Libya) at Abu-Kamash. This complex was opened in the 1970s, containing 3 units with an annual production of 104,000 tons of ethylene di-chloride, 60,000 tons of poly vinyl chloride (PVC), 50,000 tons of caustic soda and 45,000 tons of chlorine, as well as the production of sodium carbonate, sodium hypochlorite and hydrochloric acid

(Banana and Mohamed, 2016). These industrial processes also lead to the discharge of mercury into the lagoon ecosystems (Banana and Mohamed, 2016).

II.5. Urbanisation, land reclamation and coastal infrastructures

Intensive urbanization has occurred around North African lagoons. Essentially these areas are attractive for both residents and visitors, with increasing land reclamation and construction of a coastal infrastructure which enables the development of new urban areas. Thus, these regions are now highly populated, with numbers increasing annually.

Over the past 50 years, the population around the Oualidia lagoon (Morocco) has rapidly increased by 240 % from 7,741 inhabitants in 1971 to 18,616 inhabitants in 2014. The expansion of the city has modified some sedimentary forms especially the dunes on the east side of the lagoon (Yamna *et al.*, 2014). However, the most populated lagoon in Morocco is Nador, with an increase in inhabitants from 683,914 to 859,590 between 1994 and 2014 (www.hcp.ma). Recently, the Moroccan government through the “Marchica agency” has invested 4 billion Euro in seven new projects: Cité Atalayoun, Cité des 2mers, Nador new city, fisherman’s village, Baie des Flamants, Marchica Sport, Les Vergers de Marchica, which are destined as houses, apartments, a harbour, and a research centre and natural park for resident and touristic growth; some are constructed already and some are still under construction.

The inlet located at the centre of the Nador lagoon has been modified many times during the last decades (Raji *et al.*, 2013). In 2011, there was an enlargement of the inlet to a width of 300 m and a depth of 6 m to improve circulation and shipping. This included the 1450 m east breakwater and the 1350 m west breakwater (Daghor *et al.*, 2016).

Monastir lagoon (Tunisia) has been transformed by port structures, marinas, hotels, golf courses and an airport. This lagoon has been completely drained and has not been included in the list of North African lagoons (Fig.4). Tunis lagoon (Tunisia), is the most urbanized lagoon in North Africa. The population had doubled from 887,803 (2004) to 1,507,000 inhabitants (2014) (<http://dataportal.ins.tn/fr/Map>). The largest airport in Tunisia (Tunis-Carthage Airport) and military airbase have also been constructed from land reclaimed from the lagoon. Furthermore, the lagoon has been split by the construction of a road “La Goulette”, dividing the lagoon into a northerly and a southerly section.

Bizerte lagoon (Tunisia) has 4 harbors (Harbor of Bizerte, Menzel Abderrahmane harbor, Menzel Bourguiba and The Carrier bay harbour parked) (Abidli *et al.*, 2016). Furthermore, it has a massive urbanisation surrounding the lagoon (Fig.34).



Figure 34: View of urban and coastal infrastructures activities related to Bizerte lagoon

Marsa Matrouh is an important city along the 500 km Mediterranean coast between Alexandria city and the Libyan border in the north part of Egypt. It has 193,000 inhabitants which represent a density of 0.9 inhabitants km⁻² (Khaled *et al.*, 2014). The area has many five-star hotels.

II.6. Transport and shipping

North Africans societies have used and are still using lagoons for transport and shipping activities by developing harbors and marinas for commercial purposes. The shipping includes oil tankers, passenger cruise liners, packet boats, container ships, military vessels as well as smaller boats for artisanal fishing.

In the Nador lagoon (Morocco), the number of ‘feluccas’ for artisanal fishing increased by 30% from 300 to 390 between 2001 and 2012.

In the Tunisian lagoon of Bizerte, there were 997 boats in 2010, including 490 fishing boats, and 507 commercial vessels from passenger cruise liners, oil tankers, bulk carriers, container ships, gas and oil tankers, as well as military vessels. The Menzel Bourguiba harbor receives around 542 boats annually including 480 fishing “feluccas”, as well passenger cruise liners, commercial ships, ferries, and military vessels. There is also a shipyard that provides shipbuilding, maintenance and painting. The Menzel Abderrahman harbour has around 181

artisanal fishing boats (Abidli et al., 2016; Lahbib et al., 2018). The Tunis lagoon has a commercial harbor at Rades-La Goulatte used by 2902 merchant ships, including feluccas, passenger cruise liners, packet boats and container ships (Lahbib et al., 2018). The Boughrara lagoon has 50 “feluccas” in the Boughrara harbor and around 100 in Adjim harbor (Lahbib et al., 2018).

The Marsa Matrouh lagoon (Egypt) has 66 “feluccas” with no motors, 6 “feluccas” with outboard motors and 17 with inboard motors that are used for fishing with trammel nets and long lines. The small feluccas contribute 20% to the fishing activity production while larger boats contribute 80% within an annual production of around 272 tons (Mulazzani *et al.*, 2017). In the Bardawil lagoon, 1235 “feluccas” of 4 to 6 meters are used for fishing activity. The Burullus lagoon has 2098 boats where 2049 are small “feluccas” (4-6 meters), 41 are medium boats (6-8 meters), and 8 are large boats (+ 8 meters).

III. Pressures on North African Lagoons

In the context of North African lagoons, there are multiple pressures that have different forms originating from the variety of economic activities (Tables 8,9). The distribution of these pressures among the 11 selected lagoons are shown in Table 9 and more details about specific pressures are described below.

III.1. Pressures from agricultural effluents

Agriculture in the drainage basins along the coast of North Africa is responsible for contaminating lagoons with agro-chemicals such as fertilizers, pesticides and herbicides. Additionally, there are pressures from the manure derived from animal rearing.

The main pressure from the high nutrient inputs to the Oualidia lagoon in Morocco are from surface and ground waters that drain from the cultivated areas that cover 78% of the catchment (Damsiri, Elkalay and Khalil, 2015; Damsiri *et al.*, 2017) and where nitrogen and phosphate fertilizers are applied (Maanan *et al.*, 2014). These nutrients promote a significant increase in chlorophyll a within the lagoon ecosystem (El Asri et al., 2017). Another Moroccan example of pressures from agrochemicals is an irrigated, agricultural area of 92 km² (Fig.35) around the Nador lagoon (Re and Sacchi, 2017).

Table 9: *The existing pressures on North African lagoons: 'X' represents documented and '?' represents undocumented pressures. List of pressures adapted from Smith et al., (2016).*

Country	Morocco			Algeria	Tunisia			Libya	Egypt		
Lagoon	Nador	Oualidia	Khenifiss	El Mellah	Bizerte	Tunis	Boughrara	Farwa	Marsa Matrouh	Burullus	Bardawil
Smothering					X	X					X
Substratum loss						X					X
Changes in siltation	X	X				X			X	X	
Abrasion	X				X	X		X			X
Selective extraction of non-living resources	X	X								X	X
Underwater noise	X	X	X	X	X	X	X	X	X	x	X
Litter					X	X	X			X	
Thermal regime change		X			X	X	X		X	X	X
Salinity regime change	X				X	X	X		X	X	X
Introduction of synthetic compounds	X	X		X	X	X			X	X	X
Introduction of non-synthetic compounds	X	X		X	X	X	X	X	X	X	X
Introduction of radionuclides		X								X	X
Introduction of other substances	X	X		X	X	X	X	X		X	
Nitrogen and phosphorus enrichment	X	X		X	X	X	X	X	X	X	X
Input of organic matter	X	X		X	X	X	X	X	X	X	X
Introduction of microbial pathogens		X		X	X	X	X			X	X
Introduction of non-indigenous species and translocations	X	X					X				
Selective extraction of species				X	X	X	X				X
Death or injury by collision	X	X		X	?					X	
Barrier to species movement		X			X	X					
Emergence regime change											
Water flow rate changes		X			?	X	X		X		X
pH changes		X				X	X		X	X	X
Electromagnetic changes											
Change in wave exposure									X		

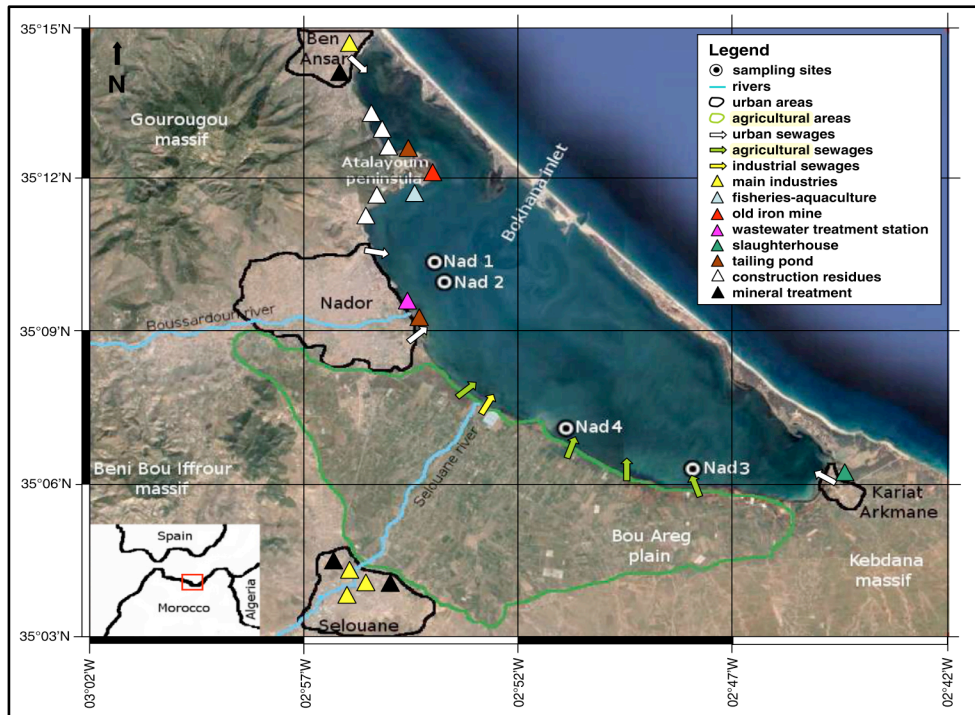


Figure 35: The most important human activities in Nador lagoon (Giuliani *et al.*, 2015a)

In the case of Algeria, many studies describe the effect of agricultural pollutants and livestock manure (Nadira, 2008) from the two rivers ‘R’kibet and El Mellah’ (Chaoui *et al.*, 2006; Magni *et al.*, 2015) on fish, molluscs and crustaceans (Mebarki *et al.*, 2015) in the El Mellah lagoon.

The pressure from runoff draining the agricultural areas around Bizerte lagoon (Tunisia) increases with rainfall in winter. Runoff contains various contaminants and pollutants including nutrients, pesticides and heavy metals (Kamel *et al.*, 2014). The increase in nutrient concentrations, especially during the wet season, stimulates phytoplankton blooms (Béjaoui *et al.*, 2017).

One of the most heavily polluted lagoons in North Africa is Burullus on the Nile delta in Egypt. Nutrient, pesticide and metal inputs come from eight streams and a canal draining from the adjacent watershed (Orabi, El-Badry and Badr-ElDin, 2017). In the southern area, there are high concentrations of tin (144 ppm) and of arsenic (44 ppm), far exceeding the World Health Organization guidelines for arsenic in soil (1.5 ppm) (El-Monsef *et al.*, 2017).

III.2. Pressures from extraction of living resources

There are multiple pressures from the extraction of living (e.g. fishing, shellfish harvest) and non-living resources, (e.g. dredging and quarrying for sand). These result in selective extraction of species, death or injury of fauna, introduction and translocation of non-indigenous species,

substratum loss, abrasion and resuspension of sediment, smothering, nutrient mobilization, underwater noise (Table 9).

The Oualidia lagoon is an ecosystem with high pressure from the extraction of living and non-living resources such as traditional fisheries (fish and molluscs), oyster aquaculture (Bocci *et al.*, 2016), seaweed harvesting and sand extraction (Beryouni *et al.*, 2012; Maanan *et al.*, 2014; El Asri *et al.*, 2015). These activities have led to pressures such as input of organic matter from aquaculture and blooms of phytoplankton (Damsiri *et al.*, 2017). Nador lagoon is also known for its aquaculture activities and fishing. The use of small mesh sizes has exerted a pressure on the fish population.

There are pressures on El Mellah lagoon (Algeria) from aquaculture with organic matter enrichment of sediment (Embarek *et al.*, 2017).

Pressures on the Boughrara lagoon (Tunisia) include organic matter from the introduction of non-indigenous species, such as the invasive species polychaete *Branchiommma bairdi* McIntosh (1885), which settles in high densities (up to 35m⁻²) on buoys and hulls of vessels (Khedhri *et al.*, 2017).

There is little information about Farwa lagoon (Libya). However, one resulting pressure of the fishing activity is underwater noise pollution (Essghaier *et al.*, 2013).

The fishing, harvesting and aquaculture extraction of living resources from Bardawil and Burullus (Fig.36) lagoons (Egypt) exert significant pressures on this ecosystem (i.e. overfishing).

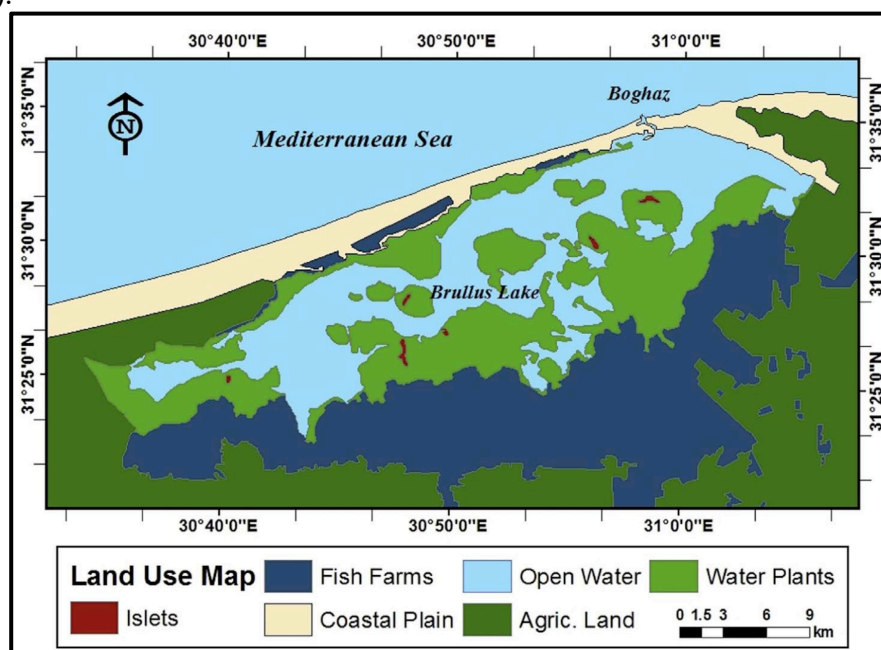


Figure. 36: Land use map of Burullus Lake area (El-Amier *et al.*, 2017)

III.3. Pressures from urban and industrial effluents

There are three types of effluent affecting lagoons including: (i) urban sewage untreated or through a wastewater treatment plant (WWTPs); (ii) urban wet weather discharges (UWWD) including rainwater, runoff water, discharges from separated stormwater system outfalls resulting from rainfall in an urbanized catchment. These flow into the lagoons without passing through a wastewater treatment system (Gooré *et al.*, 2015); and, (iii) the industrial effluents through a local or common WWTP. These pressures increase from both urban growth and climate change effects and can lead to a state change by contamination and pollution.

Some of the lagoons (Nador in Morocco, El Mellah in Algeria, Tunis in Tunisia, and Burullus in Egypt) are enriched with nutrients from agriculture (Tab.9), but there are additional pressures from urban and industrial effluents, (Tlig-Zouari and Maamouri-Mokhtar, 2008; Oczkowski *et al.*, 2008; Nassar and Gharib, 2014; Alves Martins *et al.*, 2015; Derradji *et al.*, 2015; Bocci *et al.*, 2016; Daghor *et al.*, 2016; Hammani, Brahim and Gueddari, 2016; El-Zeiny and El-Kafrawy, 2017; Khedhri, Afli and Aleya, 2017b; O. El Asri, Ramdani, Latrach, Haloui, Mohamed, *et al.*, 2017).

The increasing tourist development activities around lagoons in North Africa has also increased pressures from domestic effluents due to the seasonal increase of population, especially during the summer.

Oualidia lagoon (Morocco) is located between two cities “El Jadida” and “Safi”, adjacent to one of the biggest phosphate mines in the world and fertilizer plants. Indeed, the surface water of the lagoon is phosphate enriched (Damsiri *et al.*, 2017). Furthermore, this lagoon is known also for touristic activities, and a population increase by a factor of 4 times during summer time. This overwhelms the capacity of the WWTP, increasing the nutrient pressures. The WWTP of Nador city was built in 1980 and expanded in 1990, but it has become inadequate due to urban growth (F Ruiz *et al.*, 2006). Two new WWTP were constructed in 2010, the Grand Nador WWTP is an activated sludge plant with a daily treatment of 14 000m³ and El Aroui WWTP is a natural lagoon with a treatment capacity of 2500 m³ per day. These treatment plants are under-sized, so there are pressures from effluent into the lagoon, as well as anaerobic microbial degradation (Giuliani *et al.*, 2015a). Furthermore, there is industrial effluent coming from the Selouane industrial area that is discharged into the lagoon during the wet season. The pressures from industrial effluent (Nador lagoon) include inputs of pollutants, such as

polychlorinated biphenyls (PCB), polycyclic aromatic hydrocarbons (PCH), (Giuliani *et al.*, 2015a) and increasing inputs of polybrominated diphenyl ethers (PDE), (Piazza *et al.*, 2016).

The effluent from industries around Bizerte lagoon (Tunisia) has only primary waste water treatment (Barhoumi *et al.*, 2014; Hammani, Brahim and Gueddari, 2016). SACEM (electrical transformers) uses 900 tons of PCB (Barhoumi *et al.*, 2014). These activities have led to chemical contamination of mussels (Barhoumi *et al.*, 2014).

The Tunis lagoon is vulnerable to pressures from industrial effluent and domestic sewage due to the doubling of the local resident population during the last 10 years.

Marsa Matrouh lagoon (Egypt) is contaminated by pressures from metal pollution (Abdel Ghani, 2015) and inadequate sewage treatment due to high tourist influx (Gharib *et al.*, 2011b).

III.4. Pressures from civil engineering projects

Infrastructure for the management of the lagoons' ecosystems include artificial channels for maritime navigation of harbors and ports. Examples include the modification of inlets at Moulay Bousselham and Nador in Morocco, El Mellah in Algeria, Boughara in Tunisia, Bardawil in Egypt.

Nador lagoon (Morocco) has had a new inlet since 2011 (Fig.37) that was made to increase water exchange with the sea (Bocci *et al.*, 2016).

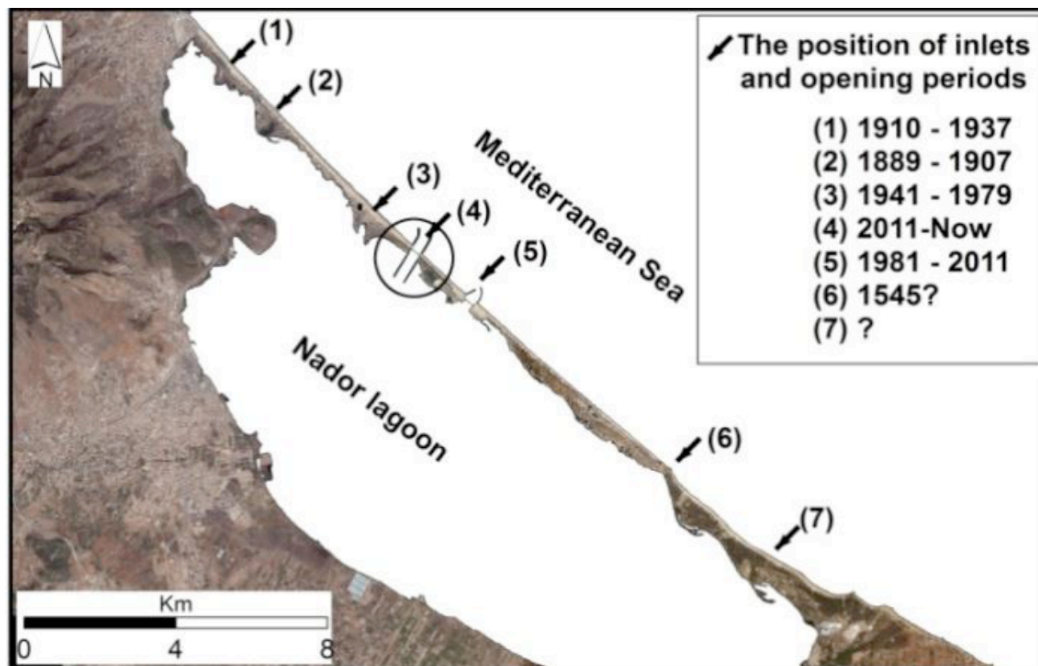


Figure 37: Historic of inlets along the barrier spit of Nador (Raji *et al.*, 2013)

Most of the modern centre of Tunis city has been built on land reclaimed from the Tunis lagoon (Thornton *et al.*, 1980). A comparison between aerial photographs and topographic maps produced between 1902 and 2020 (Fig.38).

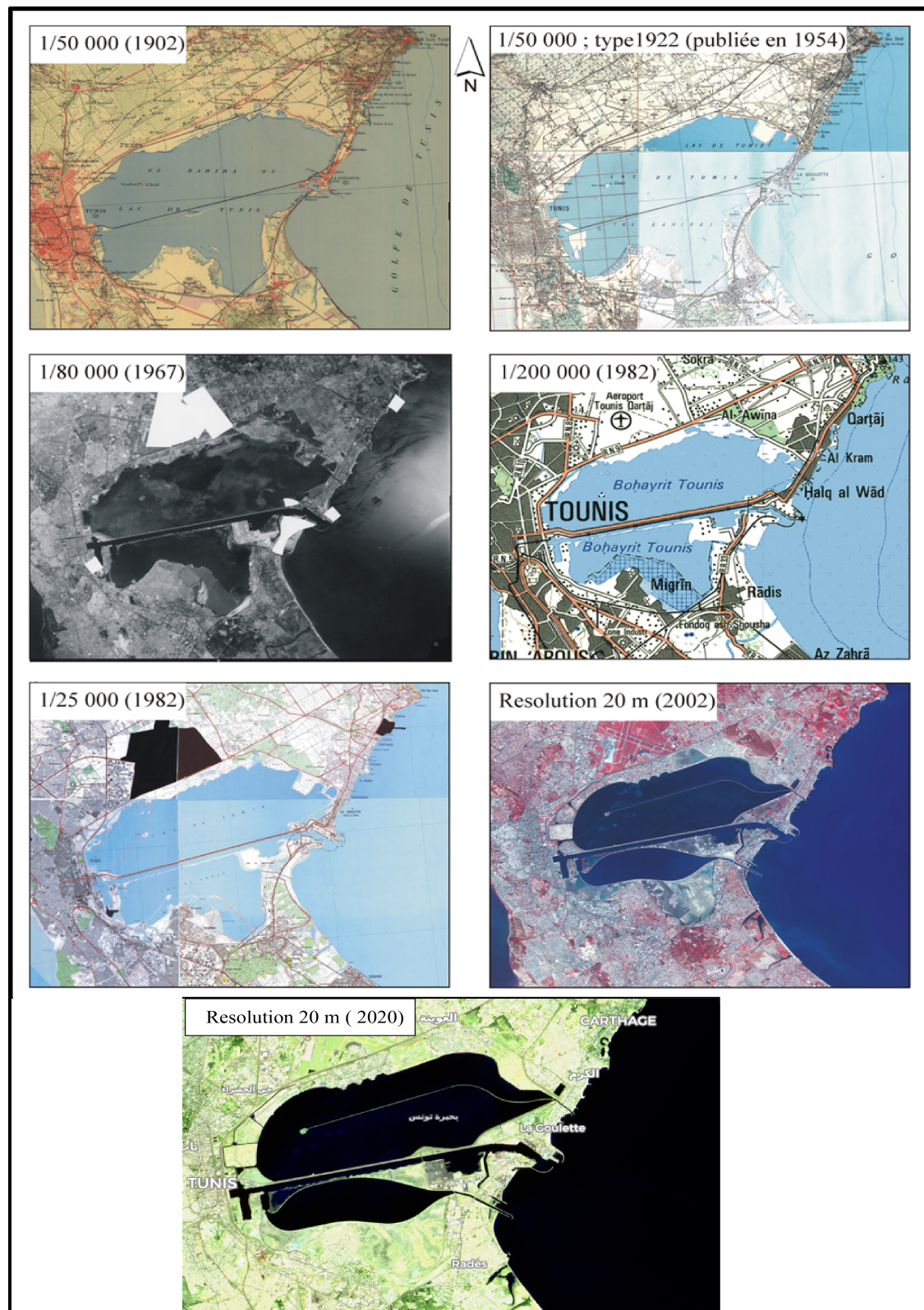


Figure 38: Satellite photos and topographic maps of Tunis lagoon between 1902 and 200. Adapted from (Chouari, 2015b)

The eastern inlet (El Kantra Channel) of Burullus lagoon (Tunisia) has been enlarged from a narrow passage of 12.5 m across in 2004 to 160 m in 2007. This has increased the daily water exchange with the sea from 0.8 million m³ to 6.9 million m³ per day (DGPA, 2001). The choking of the inlets in Bardawil lagoon (Egypt) has led to pressures such as siltation of the ecosystem that has increased significantly. It has also changed the water exchange between the sea and the lagoon, causing sedimentation at the entrance to the inlets (Nassar *et al.*, 2018).

III.5. Pressures from transport and shipping

Pressures from transport and shipping activities were found in all North African lagoons. These include: (i) underwater noise from motorized ferries, vessels and yachts; (ii) hydrocarbons from accidental oil spills from motorized boats; and (iii) anti-fouling agents that are based on organic diluters mixed with highly concentrated toxic metals such as copper and zinc (Guerra-García and García-Gómez, 2005) or tributyltin ‘TBT’ compounds.

These multiple pressures often result from conflicting interests among stakeholders, as well as from previous development and management measures for the lagoons (Lillebø, 2015). The pressures (Tab.9) result in a state change of the environment such as symptoms of eutrophication in the lagoons (e.g.: Nador in Morocco, Bizerte and Tunis in Tunisia, Bardawil in Egypt). These changes affect ecosystem services (ES) (Newton *et al.*, 2018) and can lead to an impact on human welfare.

IV. State change in North African lagoons

Human activities and modifications to North African lagoon ecosystems and their catchment areas have resulted in increased pressures that have modified the state of these ecosystems. The change of state can be at the environmental, ecological and/or ecosystem service level. Table 10 shows the state changes in lagoon ecosystems (components and processes), intermediate services (supporting and regulating services) and the final ecosystem services (provisioning, regulating and cultural) of the lagoons. No state changes have yet been detected for the protected Khenifiss lagoon, an almost pristine lagoon.

The changes to the inlets of Nador lagoon (Morocco), especially the most recent ones in 2011, have altered the hydrological processes and nutrient condition of the ecosystem. Eutrophication has stimulated algal blooms of *Caulerpa prolifera*, *Gracilaria bursa-pastoris*, and *Colpomenia sinuosa*. These changes have modified the state of ecosystem service components, intermediate services, regulating and supporting services, as well as final ecosystem services. (El Asri *et al.*, 2017a).

Table 10: The state change in North African lagoons: ‘X’ represents documented and ‘?’ undocumented state change. These are based on Elliott et al., (2017) ES classification.

Countries		Morocco			Algeria	Tunisia			Libya	Egypt		
Lagoons		Nador	Oualidia	Khenifiss	El Mellah	Bizerte	Tunis	Boughrara	Farwa	Marsa Matrouh	Burullus	Bardawil
State change												
Marine Ecosystems	Components	X	X		X	X	X	X	X	X	X	X
	Processes	X	X		X	X	X	X	?	X	X	X
Intermediate Services	Supporting	X	X		X	X	X	X	?	X	X	X
	Regulating	X	X		X	X	X	X	?	X	X	X
Final Ecosystem Services	Provisioning	X	X		X	X	X	X	X	X	X	X
	Regulating	X	X		X	X	X	X	X	X	X	X
	Cultural	?	?			?	X	X	?	X	X	X

The environmental state of El Mellah lagoon (Algeria) has been degraded by the presence of contaminants and pollutants, such as heavy metals and neurotoxic pesticides (Benradia, Berghiche and Soltani, 2016). The application of pesticides from agricultural activities and pressures from inputs of organophosphates affects the ecological state of the benthos, for example, the toxic effect of malathion on clams (Nadji *et al.*, 2010). As this is a species of economic value, the delivery of provisioning ecosystem service has declined. Furthermore, the change in salinity, due to aquaculture activities, has caused a decline in bird species diversity (2013-2017) degrading cultural services, such as bird watching (Telailia et al., 2017).

The intensive use of fertilizers on agricultural activities in the catchment area of Bizerte Lagoon (Tunisia) has modified an intermediate service through increased pressures from high inputs of nitrogen and phosphorus that have altered the state of nutrient condition and the state of phytoplankton biomass and primary production (Béjaoui *et al.*, 2017), especially, in the inner part of the lagoon. Another state change is in the hydrography and water cycling (intermediate service) of the Bizerte lagoon with an estimated deficit of -7.5Mm³ of the lagoon’s annual water flowing into the Mediterranean sea (Béjaoui *et al.*, 2017).

The subsidence land rate around Tunis lagoon, (Tunisia), is 22mm.yr⁻¹, which may lead to state change through marine submersion and flooding hazards (Ennesser, Said and Errier, 2011). The enlargement of the eastern inlet of Boughrara lagoon, (Tunisia), has not improved the environmental state or ecological state. Harmful algal blooms (HAB) have increased

organic matter accumulation and stimulated the growth of the polychaete population (Khedhri et al., 2017a), changing the state of regulating and supporting services.

Pressures from the industrial waste water of a chemical company have affected the environmental state of Farwa lagoon (Libya) that has been highly contaminated by mercury, during the period January to August 2014 (Banana and Mohamed, 2016). Marine flora (fish, cuttlefish and oyster) and fauna of the lagoon have been contaminated as high concentration of mercury were found in different species (Banana and Mohamed, 2016), impacting the provisioning and regulating services.

The Egyptian lagoons are the most affected by human activities and resulting pressures have led to significant changes in their state of environment. For instance, the large increase of water inflow from agricultural freshwater drainage (from 81.7% in 1971 to 98.18% in 2003) has changed the hydrological state of Burullus lagoon (El-Adawy *et al.*, 2013). The decrease in the environmental state of salinity has led to a change in intermediate services and final ecosystem services. The provision services of total marine fish decreased from 15.99% to 1.81% by weight (El-Adawy *et al.*, 2013). Inflow of contaminants changed the state of Burullus lagoon (Orabi, El-Badry and Badr-ELDin, 2017), where symptoms of microbial anaerobic degradation have been observed from agricultural input (Giuliani *et al.*, 2015b). A further, devastating pressure is the destruction of the dune barrier system to use the sediments for reclamation purposes (El-Asmar et al., 2013). Marsa Matrouh lagoon (Egypt) is contaminated by metals (Abdel Ghani, 2015) and domestic sewage (Gharib *et al.*, 2011b) that promote phytoplankton blooms.

Sedimentation in front of the inlets of Bardawil lagoon (Egypt) has changed the environmental state by restricting the exchange of water between the sea and the lagoon (Nassar *et al.*, 2018), which could lead to changes in the provisioning of final ecosystem services such as fishing activities. Meanwhile, the ecological state has changed because of overfishing pressures during recent decades. For instance, the crab landings increased from 754.2 tons in 2000 to 2053.1 tons in 2009, then decreased to 518.7 tons in 2014, followed by an increase to 1973.4 tons in 2015, which represents 42% of total production. There are also changes in ecological state due to a new invasive species of crab, *Callinectes sapidus* (Abdel Razek, Ismaiel and Ameran, 2016) which affects nets and netted fish. The armored dinoflagellate *Alexandrium spp.*, which is a toxic species, now accounts for 17% of total Dinophyceae taxa (El-Kassas, Nassar and Gharib, 2016).

The environmental state of sediments in Marsa Matrouh lagoon, (Egypt), has deteriorated with contamination and pollution from the trace metals vanadium, aluminium, tin, arsenic , and selenium (Abdel Ghani, 2015). This deterioration in sediment quality affects the regulating and provisioning final ecosystem services, for example high concentrations of aluminium ($100 \mu\text{g g}^{-1}$; wet wt) have been observed in the fish *Pagellus erythrinus* and which may damage it's liver (Abdel Ghani, 2015) .

V. Impact (on human welfare) in North African lagoons

Human activities and resulting pressures that cause the degradation of the environmental state, the ecological state and the delivery of ecosystem services of coastal lagoons may ultimately impact on human welfare (Tab.11). For example, lagoons are nursery habitats for juveniles of commercial species, therefore changes in the state of the environment and ecology lead to a loss of this nursery service that supports fisheries and thus provisioning ecosystem services. Impacts on human welfare are detected in most of the North African lagoons, except the Khenifiss lagoon (Morocco), which is not impacted at present. Other impacts result from toxins in Harmful Algal Blooms and the contamination of seafood by chemicals.

Civil engineering and infrastructures that modify the connectivity of most of the lagoons in the study can change the wave exposure on part of the shoreline and cause erosion. This can lead to negative impacts on the shoreline protection of the lagoon with an increased risk of flooding or storm damage to the human population due to the erosion or removal of sediment, which can aggravate conflicts among stakeholders (Conde *et al.*, 2019).

Table 11: Summary of Impacts on human welfare in North African lagoons. *X'* represents documented and '?' undocumented impacts on human welfare.

Countries	Morocco			Algeria	Tunisia			Libya	Egypt		
Lagoons	Nador	Oualidia	Khenifiss	El Mellah	Bizerte	Tunis	Boughrara	Farwa	Marsa Matrouh	Burullus	Bardawil
Provisioning	X	X		X	X	X	X	X	X	X	X
Regulating	X	X		?	X	X	?	?	X	X	?
Cultural	?	X		X	X	X	?	?	X	X	X

The Marsot aquaculture activities in Nador and Oualidia lagoons (Morocco) started in 2005 but ceased in 2010, due to environmental problems. This impacted local jobs and the availability of seafood. The presence of highly persistent pollutants, such as PCB and PAH in Nador lagoon (Morocco), has contaminated seafood and are a risk to human health (Giuliani *et al.*, 2015b). The harvesting and selling of oysters from the breeding site of Oualidia lagoon was prohibited in March 2017, by the department of Marine Fisheries of Morocco (Huffpostmaghreb, 2017) because of possible impacts on human health. The welfare of fishers of Nador lagoon was impacted by the loss of catches, leading to protests in 2018.

The degradation of environmental state due to organic over-enrichment of sediments of El Mellah lagoon (Algeria) has decreased the biodiversity and the availability of seafood in some areas, especially during the summer of 2015 (Magni *et al.*, 2015).

The pollution in Bizerte lagoon (Tunisia) affects not only the aquatic organisms but also impacts human health. For example, the mollusc disease “*Marteiliosis*” that is caused by the protozoan parasite *Marteilia spp* has infected the *Mytilus galloprovincialis*, which has impacted provisioning services of a commercial species (Elgharsalli *et al.*, 2016). Furthermore, the high concentrations of tributyltin ‘TBT’ in seafood, such as commercial species of bivalves (*R. decussatus*, *C. glaucum*, *P. nobilis* and *M. galloprovincialis*), has impacted both revenues and seafood provision (Abidli *et al.*, 2016).

The increased loading of organic matter and the presence of HAB in Boughrara lagoon (Tunisia), has caused high fish mortality and, thereby, an impact on food provisioning (Khedhri *et al.*, 2017b).

The mercury contamination from the GCCI company detected in the fish, oysters and cuttlefish in Farwa lagoon (Libya) may represent a health risk to people living in the area (Kim, Kabir and Jahan, 2016; Ha *et al.*, 2017).

The high concentrations of metals detected in fish from Marsa Matrouh lagoon (Egypt) impact both the provision of seafood and are a risk to human health (Abdel Ghani, 2015).

The chemical pollutants and salinity changes in Burullus lagoon (Egypt) have had an effect on fish diversity that has declined from 32 to 25 species (Fadili *et al.*, 2016a). This impacts the provision of commercial fish species (El-Zeiny and El-Kafrawy, 2017) to people living in the region (Orabi, El-Badry and Badr-ElDin, 2017). Furthermore, modifications to the inlet can increase the recession rates of the shoreline, which impacts the security of the inhabitants by

decreasing the sea defences (supporting service) and their livelihoods from tourism revenue (cultural service) (Nassar *et al.*, 2018).

The revenues from fisheries in the Bardawil Lagoon (Egypt), food provision and public health are threatened by HAB (Abdel Razek, Ismaiel and Ameran, 2016; El-Kassas, Nassar and Gharib, 2016).

VI. DISCUSSION

North African lagoons provide many supporting, regulation, provisioning and cultural services. Nevertheless, they are subject to numerous activities that represent sources of conflict among the different users (Newton *et al.*, 2014; Dolbeth *et al.*, 2016; Newton and Elliott, 2016; Lillebø *et al.*, 2017) producing multiple pressures that represent a negative state change on the environment and impact human welfare.

Most drivers, activities, pressures, state change and impacts (on welfare) in North African lagoons are similar to those identified in European lagoons (Newton *et al.*, 2014; Dolbeth *et al.*, 2016), due to similar activities and behavior of the stakeholders using lagoons ecosystems.

There have been several, past management responses in North Africa aimed at reducing nutrient and phosphorus enrichment, protection of the aquatic resources and developing environmental regulation to control aquaculture industries in the lagoons. These include building sewage treatments plants, improving aquatic resources, providing technical support, and monitoring and scientific research.

VI.1. Past management measures

The construction of domestic sewage treatment plants has been the main management measure in the past. Nevertheless, sewage treatment is still non-existent or inadequate for many North African lagoons.

Morocco launched a National Plan of Sanitation in 2005. As a result, Nador lagoon has two Urban Waste Water Treatment Plants (UWWTP), Moulay Bouselham and Oualidia have one, but Sidi Moussa has none. Morocco also created the National Agency for Aquaculture Development (ANDA) in 2011 which has developed environmental measures that should be followed by the aquaculture industries. ANDA is the leading actor for the aquaculture industry to promote the development of sustainable aquaculture along the Moroccan coast, including lagoons.

Algeria built a UWWTP behind El Mellah lagoon, but the water quality is still poor with respect to fecal microbes (Kherifi and Bousnoubra-Kherici, 2016). There is an unresolved conflict between the managers of the El Kala National Park and the inputters to this lagoon, mainly industries and farmers (Telailia *et al.*, 2017).

UWWTP were built in the lagoons of Bizerte, Tunis, Boughrara and Ghar El Melh (Tunisia) because of sewage contamination. Tunis lagoon was the worst affected by the contamination, but there was a restoration project in 1985 to stop pollution and eutrophication (Vandenbroeck and Rafik, 2001), and the conditions were improved by collecting waste and algae around the margin and dredging. However, the long-term monitoring plan has not been continuously maintained for nutrients and total suspended solids, but only for water temperature and salinity. Nevertheless, it highlighted sudden meteorological events (rainfalls) and/or unpredictable accidental pollution (Trabelsi *et al.*, 2013).

No data about environmental management responses in Libya has been found in this study.

The Ministry of Environment of Egypt updated the National Biodiversity, Strategy and Action Plan for the years (2015–2030) (Temraz *et al.*, 2016). This includes wetland habitats in Egypt. The targets are to reduce the rate of wetland loss by 50% by 2021, improve water efficiency in farming by 50% and develop inland water ecosystems (Finkl, 2017).

VI.2. Policy instruments with respect to North African lagoons

North African lagoons are important at the local, national and regional scale to achieve sustainable development. Regulatory authorities are responsible for monitoring programs to protect biodiversity and ecosystem services of the lagoons. This can be achieved by policy instruments to protect these ecosystems (Tab.12).

Table 12: Existing policies related to lagoons in North African countries

Morocco	Algeria	Tunisia	Libya	Egypt
<i>Law 81-12</i>	<i>Law 02-22</i>	<i>Law 95-72</i>	<i>Law 14</i>	<i>Law 9/2009</i>
Protection of coastal areas	Protection and development of the coastal areas	Agency for the planning and the protection of coastal areas	Marine protected areas	Environment protection in coastal zones

At the National level, Morocco implemented new legislation (CES, 2014) in 2014 for the protection of coastal areas, without a specific mention of lagoons. For instance, the law prohibits building on a strip of land 100m wide, adjacent to the shoreline. The new law also prohibits the discharge of wastewater, waste and any pollutants in the coastal area without specific authorization and respecting specific limits for discharges (CES, 2014). Another law that is under development calls for the conservation of fisheries ecosystems and the protection of the marine environment against pollution (Gov.ma, 2017). Morocco has created a special planning agency for the Nador Lagoon, the Agence d'Amenagement de la Marchica.

In 2002, Algeria passed legislation (JORA, 2002) for the protection and development of the coastal areas. The law includes lagoons as ecosystems, but uses the term “lido” which can be confused with coastal lakes.

Tunisia has created a special agency named, Agence de protection et d'aménagement du littoral (http://www.apal.nat.tn/site_web/index.html), for the planning and the protection of coastal areas including lagoons.

Libyan authorities issued legislation (No 14) for marine protected areas in 1992 that specifies sites that include lagoons, based on the biological, physical, and socio-economic universal criteria (Haddoud and Rawag, 1995).

The Egyptian environmental affairs agency implemented Law 4 for the protection of the environment Amended by Law 9/2009 (EEAA, 2009) to ensure the environmental protection in coastal zones as an Integrated Environmental Management of Coastal Zones without defining lagoons specifically but including them within wetlands.

At the Mediterranean region scale, there are a number of policies relevant to lagoons in the context of the management of coastal areas. These include the Ramsar convention for wetlands; the Barcelona Convention (1975) aimed at the protection of the marine environment and the coastal region of the Mediterranean; and the Integrated Coastal Zone Management 'ICZM' Protocol signed by most Mediterranean countries, except Egypt and Libya. The action plan for the ICZM protocol was implemented for the period 2011-2019, to strengthen capacities for the use of ICZM policies, instruments, tools and processes, as well as promoting the protocol within the region and worldwide.

At the global level, the United Nations defined 17 Sustainable Development Goals (SDG) and 244 indicators to be met individually and collectively by the signatory states, including North African countries (UN, 2015). Four SDGs are relevant to lagoon ecosystems both directly and

indirectly. The most relevant to lagoons is SDG 14 “*Life below Water*” followed by SDG 6 “*Clean Water and Sanitation*”, The SDG 15 “*Life and Land*” and the The SDG 13 “*Climate Action*”. North African countries should take in consideration all the provided policies and the future action in order to protect their lagoons ecosystem. Also they should established a unify framework and learn from foreign experiences as the Water Framework Directive adopted by EU countries and especially in the part of managing lagoons that are included in the transitional water categories (Newton *et al.*, 2014).

VI.3. Option for management measures

Identifying the sensitive and vulnerable zones in the lagoons allows managers to prioritize immediate measures for water bodies at risk (Ferreira *et al.*, 2006). This knowledge also allows managers to protect specific habitats, such as seagrass beds, and specific, keystone species that provide supporting and provisioning ecosystem services (e.g. food).

Once the management options have been identified, these should be checked to see whether they follow the 10-tenets approach (Elliott, 2013; Barnard and Elliott, 2015; Elliott *et al.*, 2017), to be both successful and sustainable. The measures should include both short-term and long-term plans that can deliver immediate, positive results (Tab.13), as well as mitigate and prevent future issues. One of the main short-term measures is the construction of UWWTP in some lagoons, e.g. Farwa and Ain zaina in Libya, Sidi Moussa in Morocco. The capacity of existing UWWTP is insufficient because of the seasonal increase of population due to visiting tourists. This occurs mainly summer when temperatures are high and oxygen solubility is low. Existing UWWTP can be increased in capacity or upgraded from primary to tertiary treatment, e.g. Oualidia and Tunis lagoons. The installation of nutrient removal ponds using plants such as reed beds. These measures will reduce the organic and nutrient loading into the lagoons and improve their oxygen conditions to mitigate future eutrophication. As the Mediterranean climate is hot and dry in summer, eutrophication increases during the summer and algal proliferation reaches its maximum. Effluent from UWWTP can be re-utilized as a fertilizer for some crops, e.g. fruit trees. The use of UWWTP effluent for irrigating lawns and golf courses can improve the sustainability in arid countries (Tab.13)

Another possible management measure is the construction of belt canals around the lagoons within small areas in order to intercept and divert rainwater and agricultural runoff. Moreover, increasing green areas in cities and villages and constructing uncemented cobblestone roads instead of concrete-asphalt streets can help increase the infiltration rate of rain into the soil

(Rocheta et al., 2017). Additional management measures can be implemented to restore water and sediment fluxes, especially for the lagoons with dams in the catchment and/or with inlet modifications, e.g. Moulay Bousselham in Morocco, Bizerte and Boughrara in Tunis and Marina in Egypt.

Another effective measure is monitoring and protecting surface water and groundwater from pollution sources surrounding the lagoon. This includes protecting water resources from excessive extraction, as well as contamination and pollution from runoff of agrochemicals, industrial effluents and emissions.

Management measures to reduce litter include conveniently located bins, environmental notices targeting the tourists, litter collection and cleaning of lagoon beaches in summer, e.g. Marsa Matrouh in Egypt, Oualidia and Nador in Morocco.

Land subsidence and increased risk of flooding in the area surrounding the lagoon can be avoided by an urbanization and land use plan to avoid over-construction and establish set-back lines, e.g. Tunis lagoon.

Different types and intensity of monitoring programs, surveillance operational and investigative monitoring (EU, 2000), can be implemented as a response to different risks. The monitoring plans should consider seasonality, hydrological, physio-chemical, biological and ecological aspects of the lagoons, not just focus on one aspect, such as the concentration of a pollutant.

Awareness- raising campaigns, especially for the inhabitants of the lagoon area, can be very effective. Managers can work with the local schools to organize educational field trips around the lagoons. The research group for the protection of birds in Morocco previously organized guided tours for individuals, local associations and local schools in the Oualidia lagoon to educate and raise awareness regarding the importance of lagoons ecosystems. During 2017, 1863 students and professors were introduced to the value of lagoons by this research group http://www.grepom.org/wp-content/uploads/Rapport-annuel-Activité_Centre-Walidia_2017.pdf.

Conflict management can be improved by organizing a stakeholder forums with timely stakeholder consultation to reach agreement on how to manage these ecosystems (Newton and Elliott, 2016). In Nador lagoon (Morocco), civil society confronted the Marchica development project which led to protesters questioning administration decisions regarding the prohibition of access to certain sites, the protection of local properties and the inclusion of management process.

Measures to protect culturally important areas are essential to reduce conflict between the local community and visitors. Cross-cultural sensitivity is necessary to maintain respect for local cultures and populations (e.g. typical seafood such as ‘Mussel Tagine’, and typical design of traditional boats). Cultural erosion can be mitigated through cultural adaptation, for example using traditional boats for tourism around the lagoon. The *gondolas* of Venice lagoon are an example of this, as are the *moliceiros* of Aveiro lagoon.

Economic instruments (fines, taxes, subsidies) can also be used in management. The ‘polluter pays’ principle advocated by the OECD can be used so that economic sectors are held to account if they exceed emission standards, especially for pollutants. Aquaculture, textile and oil industries are all examples of polluters within these lagoon systems.

A policy response focused on the lagoons ecosystems may result in new regulations to reduce the impact of activities and pressures from the surrounding areas.

Supporting sustainable investment by lowering taxes in order to balance economic growth, environmental awareness and actions, food security and social development which can lead to new blue economy activities such as bio-agriculture, eco-tourism, ecological shipping, organic aquaculture. This could ensure the Blue Growth related to North African lagoons.

VI.1. Knowledge gaps in North African lagoons

The analysis carried out in the present chapter revealed the lack of interdisciplinary studies on lagoons. Most studies are in specific areas, mostly in natural sciences such as biological, physicochemical, environmental, and hydrological studies with a few geological studies (Ayache et al., 2009; Flower et al., 2009; Raji et al., 2018; Ramdani et al., 2009b; Thompson et al., 2009).

North African countries need targeted but interdisciplinary studies about coastal lagoons to provide more information and knowledge in order to better understand the issues and provide more appropriate management measures. For instance, Libya has some literature reviews completed through international collaboration (Essghaier *et al.*, 2013; Mahmoud Khamis and El-Sayed El-Sayed, 2015; Banana and Mohamed, 2016), but lacks a governmental platform to provide data about the lagoons. More data are needed for all North African lagoons, especially on the relationship between the water-catchment and the lagoons that can provide more knowledge about pressures. Social, economic and even cultural studies about coastal lagoons are generally not available. These can provide more knowledge about the ecosystem services and the impact on human health and human welfare.

Table 13: Recommendation of measures in North African lagoons. *: Short-term, ** Middle term, *** long term. €€€: Costly, €€: Less Costly, €: Cheaper

What (Measure)	Where	Who (Should Implement)	Why (What Improvement)	When * /** /***	How much (Relative Cost) € / €€ / €€€
<i>Implementing WWTP</i>	– Farwa – Ain zaina – Sidi Moussa	– Ministries in charge of water and environment	– Reduce Organic and nutrient Loading – Improve oxygen conditions	*	€€€
<i>Upgrading WWTP</i>	– Oualidia – Tunis – Marsa Matruh	– Ministries in charge of water and environment	– Reduce Organic and nutrient Loading – Improve oxygen conditions	*	€
<i>Providing more garbage tins, especially during summer</i>	Lagoons that have beaches	– Urban and rural municipalities	– Ensure the cleaning of the environment and low cost in collecting garbage	*	€
<i>Identifying vulnerable and protected areas</i>	All lagoons	– Ministries in charge of water and environment	– To provide the immediate need of intervention	*	€
<i>Awareness campaign and educational fieldtrips</i>	All lagoons	– Municipalities – Education and environment ministries	– raise awareness about lagoons and their ecosystem services	**	€
<i>Construction of Belt canal around the Lagoons</i>	All lagoons	Urban and Rural municipalities	– Interception and deviation of rainfall water and agricultural drains	**	€
<i>Spatial planning : zoning (aquaculture, leisure zone .)</i>	All lagoons	– All ministries interacting in lagoons – Municipalities – Ministries of finance / justice	– control the space . – Limit stakeholder's issues	**	€
<i>licensing space for specific activities</i>	All lagoons	– All ministries interacting in lagoons – Municipalities – Ministry of finance / justice	– control each part of the lagoons . – following laws for each type of activity . – Limit stakeholder's issues	**	€
<i>Annual stakeholders consultation</i>	All lagoons	– Municipalities – All ministries	– Resolve all the existing issues and reach agreement	***	€

<i>Regulations Policies</i>	All lagoons	- All ministries interacting in lagoons - stakeholders	- Provide policies to maintain The healthy environment	***	€
<i>Implementing policies</i>	All lagoons	- All ministries interacting in lagoons - Municipalities - Ministries of finance /justice	- Ensure the respect of the provided policies	***	€
<i>Tax</i>	All lagoons	- Ministries of finance - All polluters	- Paying for restoration fees	***	€
<i>Fines</i>	All lagoons	- Ministries of finance - All polluters	- Paying for creating pollution to renovate the area	***	€ / €€ / €€€
<i>Restore water and sediment flow quantity and dynamic</i>	- Moulay Bouselham - Bizerte - Tunis - Boughrara - Marina	Ministries in charge of water and environment	- Improve water and sediment Quality and Quantity	***	€€€
<i>Implementing monitoring programs : Hydrology, biology and physicochemical parameters</i>	All lagoons	Ministries in charge of water and environment	* Provide information about existing and future risks	***	€€
<i>Protecting specific habitats and species</i>	All lagoons	Ministries in charge of water and environment	*Provide supporting ecosystem services	***	€
<i>Protection of surface water and Groundwater surrounding the lagoon</i>	All lagoons	Ministries in charge of water and environment	* Avoid future water contamination issues	***	€€€
<i>Protection of cultural areas and habits</i>	All lagoons	* Ministries of culture	*Provide more ecosystem services	***	€
<i>Re-use of WWTP</i>	All lagoons	Ministries in charge of water and environment	* Save Freshwater from extra use (Golf and Agriculture)	***	€€

VII. conclusion

This chapter mapped and analysed eleven out of twenty-two North African coastal lagoons. The most common economic sectors and human activities are the extraction of living resources (mostly, fishing) and aquaculture, followed by agriculture, transport and shipping, land-based

industries, coastal infrastructure and urbanization as secondary major activities in most of the North African lagoons.

The most common pressures in North African lagoons are underwater noise, introduction of synthetic (e.g. pesticides) and non-synthetic compounds (e.g. heavy metals), input of organic matter (e.g. sewage), as well as nutrient and phosphorus enrichment (e.g. fertilizers).

The least affected of the lagoons is Khenifiss lagoon, an almost pristine system, since it is a protected area and listed as a world heritage site for UNESCO. However, in the remaining North African lagoons, there are many state changes on the environment. These affect lagoon hydrology, salinity, connectivity, erosion and accretion, nutrient and chemical contamination, dissolved oxygen and redox potential to varying degrees. There are also many state changes in the ecology of coastal lagoons both from the ecological components and ecosystem processes, which include intermediate services (supporting and regulating services) and the final ecosystem services (provisioning, regulating and cultural). These changes have led to an impact on human welfare, especially in provisioning services (e.g. revenue from catches and provision of food) and other impacts on human welfare such as health (contaminated seafood).

Lack of knowledge about the value of lagoon ecosystem services and the impacts on human welfare hampers the sustainable management of North African lagoons. Some immediate responses as management measures, such as improving UWWTP could be implemented by North African countries. The complexity of the lagoon systems also calls for the adoption of participatory methods that include all stakeholders in order to manage the multiple issues affecting the social, economic and ecosystem services of these important environments. This can foster a more transdisciplinary approach and improve the implementation of policies aimed at coastal protection and improving ecosystem services. An investment in sustainable extraction of resources, bio-agriculture, tourism, ecological transport and shipping and raising awareness could ensure the Blue Growth of the lagoons in North Africa benefiting both the surrounding population and the ecology.

In summary, DAPSI(W)R(M) is an adaptive management framework for social- ecological systems that could provide options for supporting decision makers in North Africa with science-based knowledge to deliver sustainable development to the North African lagoons

CHAPTER 2: CONTRIBUTION OF RS TO HOLISTIC COASTAL AND MARINE ENVIRONMENTAL MANAGEMENT FRAMEWORK

Obtaining environmental data is necessary to use these frameworks is difficult, especially in countries where access to reliable data and their dissemination are limited or non-existent (Kennedy *et al.*, 2009) and even thwarted. (Ndzabandzaba, 2015) raised awareness of the Global Sustainable Development Report regarding data sharing and their essential role in decision-making and as a key for further progress. For instance, the European Union Directives (e.g., Water Framework Directive (WFD) (European Commission, 2000) and Marine Strategy Framework Directive (MSFD) (European Commission, 2008)) require continuous environmental monitoring and sharing data in a consistent and transparent manner (Agency, 2013), despite the complexity and cost of this obligation. Furthermore, countries worldwide that are signatories to Regional Sea conventions (e.g., OSPAR, HELCOM, and Barcelona Convention) must also monitor accordingly. For this purpose, these countries are mainly using the targets of the Sustainable Development Goals (SDGs) (Nations, 2015, 2016) and the goals of the Ocean Health Index (OHI) (Halpern *et al.*, 2012).

The results below show the RS applications for the interconnections between DAPSI(W)R(M) and RS technologies, focusing on each component of the framework. This information will help to fill the knowledge gap required to achieve holistic, integrated coastal and marine management.

The findings that are presented in Tables 14, 15, and 16 are of potential value for decision-makers, researchers, managers, engineers, and other stakeholders working on technical aspects. For example, a coastal manager working on eutrophication may be interested in assessing how much intensive agriculture there is in a catchment. The manager can choose to use “area of greenhouses” as an indicator of intensive agriculture. Using Table 14, the manager can find the research developed by (Yang *et al.*, 2017). However, the manager can also find the research of (Aguilar *et al.*, 2015) in Table 15 (pressures section), which can provide information about the type of crop, as well as provide some information about the quantity of fertilizer and nutrient ratios shown by the research of (D. Wang *et al.*, 2018). Furthermore, the manager can also assess the distribution of harmful algal blooms as a state change in Table 16, and follow the techniques used by (Blondeau-Patissier *et al.*, 2014).

I. RS and driving activities

Remote sensing technologies have transformed research in many sectors related to coastal and marine areas. Table 14 summarizes the recent advanced application of remote sensing in relation to the main activities in key economic sectors in marine and coastal areas (Fig.31).

Table 14: *A review of the remote sensing applications that are being developed for activities related to the economic sectors in coastal and marine areas.*

Sector	Type of Activity	RS technology	If SRS Data	Description /Application	Reference	Environment
		SRS, ARS, UAV, USV, UUV, SS	Satellite			Coastal /Marine
General				Remote sensing for marine management	(Fingas, 2019b)	C /M
Agriculture	General	SRS	-	Monitoring of agricultural landscapes	(Corgne, Hubert-Moy and Betbeder, 2016)	C
		SRS	-	SAR for agriculture applications: Review	(LIU <i>et al.</i> , 2019)	C
		SRS	-	A comparison of eight global and regional agricultural monitoring systems	(Fritz <i>et al.</i> , 2019)	C
	Coastal Forestry	SRS	Landsat	Visualizing coastal forest dynamics by SRS	(Beitl <i>et al.</i> , 2019)	C
	Coastal Farming (Greenhouses)	SRS	Landsat and Worldview 2	Detection of horticultural crops under greenhouses using multi-temporal SRS	(Aguilar <i>et al.</i> , 2015)	C
		SRS	Landsat ETM+	Developing a new spectral index for mapping greenhouse using medium spatial resolution SRS	(Yang <i>et al.</i> , 2017)	C
Livestock		UAV	-	Detecting livestock in UAV images	(Kellenberger, Marcos and Tuia, 2018)	C
Golf		SRS	SPOT 5	Golf course detection using multispectral remote sensing imagery	(J. Chen <i>et al.</i> , 2017)	C
Damming		SRS	Sentinel 1	Deformation effects of dams on coastal regions using sentinel-1 images	(Karamvasis and	C

					Karathanassi, 2017)	
Aquaculture	General	SRS	-	Aquaculture: Relevance, distribution, impacts and spatial assessments—a review	(Ottinger, Clauss and Kuenzer, 2016)	C/M
		UUV	-	Integrated navigation for autonomous underwater vehicles in aquaculture: A review	(J. Bao <i>et al.</i> , 2019)	M
	Tank	SS	-	Static sensors for monitoring the water quality and fish behaviour in aquaculture tanks	(Parra <i>et al.</i> , 2018)	C/M
	Ponds	SRS	Landsat/Sentinel 1	Remote monitoring of expansion of aquaculture ponds along a coastal region	(Ren <i>et al.</i> , 2018)	C
	Shellfishery	SRS ARS	TerraSAR-X/SPOT 5 and Hypspx	Hyperspectral remote sensing of wild oyster reefs	(Le Bris <i>et al.</i> , 2016)	C/M
Extraction of Living Resources	Fishing	SRS/ARS/USV	-	Fisheries applications of remote sensing: An overview	(Klemas, 2013)	M
	Seaweed and saltmarsh harvesting	SRS	-	The remote sensing of biodiversity: from global to local scales	(Heumann <i>et al.</i> , 2018)	C/M
Extraction of Non-Living Resources	Coastal sand mining	SRS	ALOS	Characterization of black sand mining activities using remote sensing	(Chaussard and Kerosky, 2016)	C
	Onshore mineral extraction	SRS	-	Assessing impacts of mining: Recent contributions from GIS and remote sensing	(Werner, Bebbington and Gregory, 2019)	C
Tourism and Recreation	General	SRS/ARS UAV	-	Interaction between a protected destination system and conservation tourism through RS	(Miller <i>et al.</i> , 2018)	C/M
		SRS	Worldview 2	Integrating machine learning techniques and high-resolution RSR imagery to generate GIS-ready information for urban water consumption	(Wolf and Hof, 2012)	C
	Swimming pool	ARS	-	ARS data to support the estimation of water use in private swimming pools	(Llausàs <i>et al.</i> , 2018)	C

	Beach use	SRS	Landsat 8 Sentinel-2	Characterizing beach changes using SRS	(Cabezas <i>et al.</i> , 2019; Cabezas <i>et al.</i> , 2019)	C
		UAV	-	Monitoring beach topography and its change using UAVs imagery	(Chen <i>et al.</i> , 2018)	C
	Tourism Resort	ARS		Estimating the annual carbon budget of a weekend tourist resort	(Sung, Cho and Hong, 2015)	C
Land-Based Industry	Desalination	SRS	-	Characteristics of satellites commonly used for desalination monitoring	(Al Shehhi <i>et al.</i> , 2017)	C/M
		SRS	MODIS	Exploring MODIS to assess and monitor desalination impact	(Muhairi <i>et al.</i> , 2009)	C/M
Coastal Infrastructures	Cross-Sea Bridge	SRS	MODIS	Impact of coastal infrastructure on RS products using MODIS data	(Yuan <i>et al.</i> , 2019)	C/M
	Marina	ARS	-	Identifying the environmental impact of a marina development using ARS	(Klein and Zviely, 2001)	C/M
	Port	SS	-	Static Sensors network integration to estimate harbour activity impact	(Merico, Dinoi and Contini, 2019)	C/M
		SRS	-	Use of satellite imagery for water quality studies in New York Harbor	(Hellweger <i>et al.</i> , 2004)	C/M
		ARS		Assessing the impact of sea-level rise on port operability using LiDAR-derived digital elevation models	(Gracia <i>et al.</i> , 2019)	C/M
	Beach nourishment	SRS	-	Sub-annual to multi-decadal shoreline variability from publicly available SRS	(Vos <i>et al.</i> , 2019)	C
Navigational Dredging	General	SRS	Landsat-8 Sentinel-2A WorldView 2 WorldView-3 GeoEye-1	Assessment of turbidity plumes during dredging operations using SRS	(Caballero, Navarro and Ruiz, 2018)	C/M

Transport and Shipping	General	SRS	Optical Satellite	Vessel detection and classification using SRS optical imagery: A literature survey	(Kanjir, Greidanus and Oštir, 2018)	M
		SRS	SAR	Maritime vessel classification to monitor fisheries with SAR images	(Xiao <i>et al.</i> , 2018)	M
Renewable Energy	Wind farms	SRS	Radarsat-2	Offshore winds mapped from satellite remote sensing	(Hasager, 2014)	M
Non-Renewable Energy	Fossil fuel energy (Oil/Gas)	UUV/USV	-	Application of robotics in offshore oil and gas industry	(Shukla and Karki, 2016)	M
		SRS/ARS	Jers Radarsat-1, Envisat, ...	Assessing offshore oil/gas platform status using SRS and ARS time-series images	(Liu <i>et al.</i> , 2018)	C/M
	Nuclear energy	SRS	Landsat TM and ETM+	Application of SRS data for Monitoring Thermal Discharge Pollution from a Nuclear Power Plant	(Dai <i>et al.</i> , 2012)	C/M
Carbon Capture and Storage	General	SRS/ARS	-	RS technologies for monitoring geologic storage operations	(Litynski <i>et al.</i> , 2013)	C
Research and Education	Marine archaeology	SRS/ARS		ARS and SRS for archaeological and cultural heritage applications: A review of the century (1907–2017)	(Luo <i>et al.</i> , 2019)	C/M
Land Reclamation	-	SRS	Sentinal-1	Impacts of land reclamation assessed with Sentinel-1: The Rize (Turkey)	(Erten and Rossi, 2019)	C/M
Military	General	SRS	DigitalGlobe and MODIS	Evidence of environmental changes caused by Chinese island-building using SRS	(Smith <i>et al.</i> , 2019)	M
	Munition test and use	UUV	-	Spread, behaviour, and ecosystem consequences of conventional munitions compounds in coastal marine waters	(Beck <i>et al.</i> , 2018)	M

I.1. Agriculture

Agriculture activity is essential for food security. However, agricultural production is considered as the single most extensive form of land use on the planet, occupying more than

40% of its area (Campbell *et al.*, 2017). There are many types of agriculture activities that can be found in the coastal zones (e.g., extensive cereal farming and intensive greenhouse farming).

Remote sensing technologies have been a useful tool for assessing agricultural targets, such as the monitoring of soil properties, crop classification, monitoring and crop stress, supporting decisions on irrigation, fertilization, and pest management for production (Huang *et al.*, 2018). Recently, (Corgne, Hubert-Moy and Betbeder, 2016) reviewed RS data for agricultural landscape monitoring. (LIU *et al.*, 2019) analysed the existing issues, latest advances, and future directions in synthetic aperture radar used on agriculture fields as SRS. (Fritz *et al.*, 2019) compared eight global and regional agricultural monitoring systems that use RS.

I.1.1. Coastal Forestry

Coastal forests deliver many benefits, such as preserving biodiversity, conserving water and land resources, carbon storage, storm protection, and many other products (Mattsson *et al.*, 2009). They can be natural or human-made and exist in different forms, such as mangroves, beach forests, peat swamp forests, riparian forests, periodic swamps, and many others. (Beitl *et al.*, 2019) combined Landsat images of 30 years in an analysis to quantify the patterns of cover change of mangrove forest in Ecuador.

I.1.2. Coastal Farming—Greenhouses

The numbers of plastic-covered greenhouses have been increasing drastically in the last decades, especially in coastal areas, showing the evolution from traditional to industrial farming styles. Their detection and mapping via RS are still a complex task. (Aguilar *et al.*, 2015) derived several agricultural features from Landsat 8 and WorldView-2 SRS data, which allowed him to detect the four most popular autumn crops in greenhouses in Almeria, Spain. (Yang *et al.*, 2017) proposed a new plastic greenhouse index using medium spatial resolution satellite data, such as Landsat Enhanced Thematic Mapper Plus (ETM+) images.

I.1.3. Livestock

Livestock rearing is an important activity that contributes to the input of organic matter and nutrients, and its production has increased rapidly in recent decades. UAVs are good tools to estimate livestock. (Kellenberger, Marcos and Tuia, 2018) addressed animal detection through UAVs and used a Convolutional Neural Network to increase the detection of animals located in fields.

I.1.4. Golf

Golf practice has increased in popularity during the last decades and the number of golf courses has grown rapidly. This exerts multiple pressures on the environment using fertilizers, pesticide, and water (Salgot and Tapias, 2006). Based on landscape metrics using multispectral medium-resolution SRS imagery from SPOT 5 images, (J. Chen *et al.*, 2017) proposed a practical bottom-up approach to detect golf courses.

I.2. Damming

Building dams along rivers that end downstream to the coast is increasing with time (Milliman, 1997; Syvitski and Kettner, 2011). (Ezcurra *et al.*, 2019) demonstrated the impact on the physical processes and biodiversity of coastal zones, such as coastal erosion, loss of habitat for fisheries, and the release of carbon sequestered in coastal sediments. (Karamvavis and Karathanassi, 2017) used Sentinel-1 TOPS data through the application of Persistent Scatterer Interferometry methodologies for mapping and measuring dynamic patterns changes of coastal topography in the West Lesvos in Greece, which also showed a reduction in fluvial sediment supply.

I.3. Aquaculture

Aquaculture is becoming one of the principal sources of aquatic proteins worldwide due to the rise of the human population and the high demand for aquatic protein that can be found inland, the coast, and the sea (FAO, 2018). It is also a major sector for Blue Growth (EU, 2017). There are three types of areas for its cultivation, namely freshwater (lakes, rivers), brackish water (lagoon, estuary), and marine waters (fjords, open water). RS technologies are useful tools for site selection and/or detection and monitoring of aquaculture sites (Singh and Parida, 2018). (Ottinger, Clauss and Kuenzer, 2016) provided a review of recent studies that used satellite images for the assessment of aquaculture and also presented their potentials and opportunities. (J. Bao *et al.*, 2019) reviewed the latest advances of UUVs and recommended the development of their integrated navigation systems.

Furthermore, aquaculture production includes many types of cultivation systems, such as cages and pens, tanks, ponds, nets, longlines, and intertidal shellfish culture. (Bostock *et al.*, 2010) and (Troell *et al.*, 2013) provide some examples of cultivation types and the role of RS for their detection and monitoring. However, this excludes pens and longlines as it is still difficult to detect them from long-distance sensors (SRS, ARS, and UVS).

I.3.1. Tanks

There is an increasing demand for tanks by aquatic industries, which are increasingly getting larger (Espmark *et al.*, 2017), thereby requiring improvements to the monitoring of the conditions for fish culture. (Parra *et al.*, 2018) proposed a set of SS using wireless sensor networks in aquaculture tanks for monitoring the water quality and fish behaviour during the feeding procedures.

I.3.2. Ponds

Ponds have been rapidly expanding during the last decades within fertile coastal zones. SRS can be used to quantitatively assess the expansion of the pond's land use and its impact on the coastal environment using satellite images, such as Landsat for long time series analysis (Ren *et al.*, 2018) and/or Sentinel-1 (Prasad *et al.*, 2019).

I.3.3. Shellfish Culture

Shellfish culture produces essentially bivalve molluscs, such as oysters, mussels, and clams. (Le Bris *et al.*, 2016) used hyperspectral and multispectral data by combining SRS images (TerraSAR-X and SPOT 5) and ARS images (Hypex) to map wild oysters' reefs and provide an estimation of their stocks.

I.4. Extraction of living resources

Extraction of living resources in marine and coastal areas can be represented in different ways, such as fishing, seaweed harvesting, and saltmarsh vegetation harvesting.

I.4.1. Fishing

There is a high demand for fish protein, but the productivity of fisheries is in decline worldwide. RS technologies are used for both guiding vessels to locate fishes and monitoring fishing vessels to manage fisheries with the help of SRS, ARS SS, and USVs. (Klemas, 2013) reviewed the fisheries application of RS and described their importance and their combination with forecast models on improving the extraction and the management of fisheries resources. (Laurs, Foley and Musyl, 2006) used SS and USVs connected to the Argos satellite system to tag large pelagic marine fish (tuna, billfish, and sharks). Furthermore, SRS, such as the VIIRS Visible Infrared Imaging Radiometer Suite developed by NASA/NOAA, is a widely used tool for fish detection (Elvidge *et al.*, 2018).

I.4.2. Seaweed and Saltmarsh Vegetation Harvesting

Aquatic vegetation support and maintain the ecosystem functions, produce goods and services, and provide many societal benefits. SRS is an important tool for their assessment, detection, as well as monitoring of harvesting activities (Heumann *et al.*, 2018).

I.5. Extraction of non-living resources

The extraction of non-living resources in different forms on the coast and at seas, such as sand mining and offshore mineral extraction, which are important activities for Blue Growth (EU, 2017).

I.5.1. Coastal Sand Mining

This activity provides incomes to contractors and inexpensive materials for the construction industry (Jonah *et al.*, 2015) due to the relatively simple extraction process. (Chaussard and Kerosky, 2016) used optical SRS data to identify legal and illegal mining sites in the black sand beach of the Philippines and used Interferometric Synthetic Aperture Radar as SRS to evaluate their environmental impacts.

I.5.2. Onshore Mineral Extraction

This activity can be found near to the coast and it can impact biodiversity. (Werner, Bebbington and Gregory, 2019) reviewed the recent contribution of RS technologies (SRS, ARS, and UAV) to assess the impact on mining extraction.

I.6. Tourism and recreation

There is a range of activities on the coast and sea related to tourism and recreation, which can be monitored using RS data such as coastal swimming pool use, beach use, resort construction, and many others.

I.6.1. Swimming Pools

Swimming pools place extra burdens on local water supply systems and intensify water scarcity. For instance, in coastal rural areas, swimming pools may be using unlicensed boreholes for their water supply. Swimming pools in residential areas can be assessed with different RS data by using SRS, ARS, and UAVs. (Llausàs *et al.*, 2018) used LIDAR data as an ARS application from the cadastre of Barcelona city to estimate water use for private swimming pools along the coast of the city. (Wolf and Hof, 2012) performed machine learning techniques integrated with high-resolution SRS imagery derived from Worldview 2 data to

generate information regarding urban water consumption, including swimming pool assessment.

I.6.2. Beach Use

Beach tourism can lead to the degradation of coastal ecosystems. Research on beach use has become more collaborative, with the increased use of RS data and for the protection of natural values of coastal ecosystems (Prodger *et al.*, 2016; Jackson and Nordstrom, 2019). The high-resolution images of UAVs support topographic surveys and detect geomorphic changes in complex beach terrains. However, there are limitations on data coverage and the loss in vertical accuracy induced by external factors (Chen *et al.*, 2018). SRS is largely used for the detection of beach changes. (Cabezas-Rabadán, Pardo-Pascual, Almonacid-Caballer, *et al.*, 2019) proposed a new perspective for using Satellite-Derived Shorelines (SDS) from Landsat 8 data to manage microtidal beaches with high tourism influx, such as the case of Valencia, Spain. For the same region, (Cabezas-Rabadán, Pardo-Pascual, Palomar-Vázquez, *et al.*, 2019) proposed a detailed characterization of beach changes using SDS derived from Sentinel-2 data as an automatic, massive, and efficient shoreline extraction tool to derive beach width as an indicator of beach morphology.

I.6.3. Tourist Resort

Many tourist operators focus on providing a large number of activities inside and outside their buildings, to retain a large number of tourists in the resort by meeting their vacation needs. Such a concentration of numbers and activities in a small area presents management challenges similar to that of a small town (Palmer and Mathel, 2010). (Sung, Cho and Hong, 2015) used ARS images to estimate the annual carbon budget from emission and sequestration of a weekend tourist resort in Korea by using LIDAR data combined with visitor surveys and energy consumption data.

Furthermore, (Miller *et al.*, 2018) provided an overview of the benefits of RS data for supporting the sustainability of Protected Destination Systems (PDSs) as ecological touristic spaces that can be taken as good practices in coastal tourism.

I.7. Land-based industry

Many types of industries can be found in coastal areas, especially in the vicinity of ports. Industrial activities produce several environmental and socio-economic impacts that can be analysed using RS technologies by assessing their effluents and use of resources from land,

fresh, and marine waters. There has been an unprecedented increase in desalination plants to meet the global demand for water.

I.7.1. Desalination

The plants are broadly distributed along coastlines worldwide. The common impacts of their effluent are water intakes, sea outfall discharges, and harmful algal blooms that can be detected and monitored through the potential use of RS. For a large-scale area, (Muhairi *et al.*, 2009) used MODIS visible and thermal channels as an SRS application to assess the impact in the Arabian Gulf. (Al Shehhi, Gherboudj and Ghedira, 2017) provided a list of satellites commonly used in ocean colour applications and their characteristics, and (Anderson, Boerlage and Dixon, 2017) presented a guide to the management of desalination impacts.

I.8. Coastal infrastructures

Coastal infrastructure refers to structures built along coastlines, such as cross-sea bridges in regional seas (e.g., Øresund bridge), marinas, ports, seawalls, groynes, jetties, piers, and many others.

I.8.1. Cross-Sea Bridges

This type of infrastructure can bring huge benefits to the connected regions for social and economic development, but also create an environmental impact. (Yuan, Jalón-Rojas and Wang, 2019) showed the impact of these infrastructures on ocean colour RS data by using MODIS images.

I.8.2. Marinas

The increase of these coastal infrastructures has accelerated in the late 20th century and early 21st century along all coastlines of the world. (Klein and Zviely, 2001) provided an approach to assessing marina development and showed their impact on adjacent beaches using ARS images.

I.8.3. Ports

In particular, shipping ports are important transport hubs in the global supply chain of goods. Building such infrastructure attracts investors and there is an increasing competition between countries and regions for the deep-water “Panamax” ports that are needed for giant or mega container ships, or Very Large Crude Carriers (VLCC). (Merico, Dinoi and Contini, 2019) presented a network approach for low-cost static sensors (SS) that operates in near-real-time data to assess shipping traffic impact and harbour-related activities with a major concern for air quality. SRS can support the assessment of water quality related to harbours despite the

complexity of their hydrography and the influence of tides. (Hellweger *et al.*, 2004) compared different SRS images using time-averaged spatial analysis to assess many parameters related to the impact of New York Harbor. ARS hyperspectral images can also support monitoring of water quality in harbours (Trees *et al.*, 2005). Furthermore, (Gracia *et al.*, 2019) deployed ARS using LiDAR-derived digital elevation to assess port infrastructure and its operability under scenarios of sea-level rise.

I.8.4. Beach Nourishment

Nourishment of beaches with sand is used to reduce coastal erosion (Semeoshenkova and Newton, 2015; Danovaro *et al.*, 2018) and to attract tourists (Pranzini *et al.*, 2016). (Vos *et al.*, 2019) assessed different sandy beaches from different parts of the world to quantify the changes in shorelines using different accessible, free SRS data combined with in situ data, and provided a list of major civilian satellites to measure the impact of this activity.

I.9. Navigational dredging

Shipping activities involve dredging operations to maintain navigational access and this can contribute to the loss of habitat, due both to the removal of substrates and to lethal or sublethal stress caused by elevated sedimentation and turbidity (Erftemeijer *et al.*, 2012). There are also large areas where the dredged sediments may be stored, especially if they are contaminated. Many SRS-based approaches have been used to assess the impacts. (Caballero, Navarro and Ruiz, 2018) combined five public and commercial medium- and high-resolution satellites that allowed cost-effective monitoring of turbidity plumes during dredging processes, including WorldView-2, WorldView-3, Landsat-8, Sentinel-2A, and GeoEye-1 SRS.

I.10. Transport and Shipping

The maritime transport and shipping sectors have shown an exponential increase in the number of vessels used to transport people and goods crossing different seas around the world (An, Choi and Lee, 2019). (Kanjir, Greidanus and Oštir, 2018) presented a literature survey of 30 years of research on ship detection and classification using optical SRS imagery and presented positive and negative aspects of each type of detection method, which allowed them to predict future trends for this area of SRS applications. (Xiao *et al.*, 2018) used SAR images (SRS) to distinguish between fishing and non-fishing vessels based on the Random Forest approach in order to tackle overfishing issues.

I.11. Renewable energy

Renewable energy may be generated in different ways, namely offshore wind, tides, ocean currents, and waves. Wind farms are the most common (Weiss *et al.*, 2018). They have been growing due to the environmental conditions along the coasts and in the sea (Calaudi *et al.*, 2016). However, the installation of offshore wind farms and their operation can degrade the sea floor and create artificial reefs. Their impact on the sustainability of the sea needs to be assessed (Schwanitz, Wierling and Shah, 2017). (Hasager, 2014) showed the potential of high-resolution SAR data from RADARSAT-2 SRS to map offshore wind farms and to detect wakes from long and far-field wind farms.

I.12. Non-renewable energy

I.12.1. Fossil Fuels (Oil and Gas)

Offshore oil and gas operations present various environmental hazards due to drilling and spills, as well as major accidents (Necci *et al.*, 2019). RS technologies can help to avoid both human and environmental threats. (Shukla and Karki, 2016) reviewed the application of USVs and UUVs to survey offshore sites, an inspection that requires remote assistance as well as surveillance for preventing and cleaning up oil spills. (Liu *et al.*, 2018) used a time-series RS approach to assess offshore oil and gas platforms status by combining 26,000 SRS and ARS images from JERS, RADARSAT-1, ENVISAT, ALSO (PALASAR), Landsat Collection, and (S-NPP) VIIRS SRS, as well as from the National Agriculture Imagery Program (NAIP) aerial images. This approach detected 9260 platforms and determined installation and removal dates.

I.12.2. Nuclear Power

Nuclear power plants are often located on coasts to use the seawater for cooling. This entails some risks, such as the 2011 Fukushima Daiichi accident after a tsunami caused by the Sendai earthquake in Japan. However, many others are at risk from erosion, rising sea-levels, and storm surges; a well-known example being Hinkley Point in the UK. Nevertheless, normal operation causes thermal discharge pollution that has a significant impact on the coastal environments and marine ecosystems (Hejazi, 2017). (Dai *et al.*, 2012) used a multi-temporal Landsat band six thermal infrared SRS images to assess the spatial diffusion of thermal discharge and to quantify the variability of sea surface temperatures.

I.13. Carbon capture and storage

Carbon capture and storage (CCS) is one option to reduce the CO₂ from emissions. There is growing interest and investment, but there are uncertainties with respect to adapted technologies, engineering performance, and natural hazards (S. Zhang *et al.*, 2019). The U.S. Department of Energy, National Energy Technology Laboratory, has developed many applications of RS technologies to monitor storage operations, including SRS, ARS (LiDAR), and USV (Litynski *et al.*, 2013) to assess CCS. The full list of technologies is provided by (Litynski *et al.*, 2013).

I.14. Marine archeology

Marine archaeologists have identified several marine archaeological sites, especially with the use of RS technologies such as SRS and UUVs to detect the objects and features of these sites (McCoy, 2018; Tapete, 2018; Benjamin *et al.*, 2019). (Luo *et al.*, 2019) reviewed a century of SRS and ARS applications for archaeological research, including the coast and the sea.

I.15. Land reclamation

Land-use change and reclamation of coastal areas have increased due to increasing pressure in the coastal zone, especially for agriculture, aquaculture, urbanization, industrial plants, infrastructure such as airports, and even artificial islands (Duan *et al.*, 2016). (Martín-Antón *et al.*, 2016) assessed the world's land reclamation situation using Google Earth and showed that the highest development exists in East Asian countries (China, Japan, and Korea). (Zhang, Su and Ding, 2017) focused especially on the South China Sea, using SRS from Landsat to assess the situation between 1975 and 2010. Pressures from land reclamation activities lead to environmental change and degradation of coastal natural habitats, such as wetlands and dunes. RS can be used to measure changes and monitor reclaimed land and coastline length (W. Chen *et al.*, 2017; Splinter, Harley and Turner, 2018; Doxaran *et al.*, 2019). (Erten and Rossi, 2019) used SRS from Sentinel-1 images to detect and assess subtle land displacements to monitor small areas with high risk.

I.16. Military

For the military, mostly the Navy, infrastructure on the coast is growing due to being strategically important, and recently many new structures have been revealed through satellite images. (Smith *et al.*, 2019) presented evidence of environmental changes from a military base built on artificial islands on the South China Sea by using SRS data from DigitalGlobe and

MODIS images. Furthermore, another issue resulting from military activities in coastal marine environments is the intentional disposal of unexploded ordnance and munitions that contain organic explosives and a variety of metals. These can be assessed by RS technologies (USV and UUV) using Multibeam sonar, sub-bottom profiling, and magnetometry (Beck *et al.*, 2018).

II. RS and pressures

The increasing influence of human activities on the coast and the ocean leads to a variety of anthropogenic pressures combined with natural pressures, which make them hotspots of global change (Newton, Carruthers and Icely, 2012; Newton *et al.*, 2020). Recent advances in remote sensing technologies (RS) can help in mapping and assessing the pressures. Table 15 summarizes the recent advanced application of RS in relation to the main pressures that can be found in marine and coastal areas and their usefulness regarding WFD indicators, MSFD descriptors, UN SDGs targets, and OHI goals.

For WFD, there are three main indicators: Biological Quality Elements (BQE), Physico-Chemical Quality Elements (P-CQE), and Hydromorphological Quality Elements (HQE) (see https://ec.europa.eu/environment/water/water-framework/index_en.html).

For MSFD, there are eleven related descriptors: D1—biological diversity; D2—non-indigenous species; D3—fisheries; D4—food webs; D5—eutrophication; D6—seafloor integrity; D7—hydrographical conditions; D8—contaminants; D9—contaminants in seafood; D10—marine litter; and D11—energy and noise (see https://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm).

For the SDGs, there are seventeen goals: SDG1—no poverty; SDG2—zero hunger; SDG3—good health and well-being; SDG4—quality education; SDG5—gender equality; SDG6—clean water and sanitation; SDG7—affordable and clean energy; SDG8—decent work and economic growth; SDG9—industry, innovation, and infrastructures; SDG10—reduced inequality; SDG11—sustainable cities and communities; SDG12—responsible consumption; SDG13—climate action; SDG14—life below water; SDG15—life on land; SDG16—peace justice and strong institutions; and SDG17—partnerships for the goals. Furthermore, each goal has specific targets (e.g., T14.1 is the first target of SDG 14, and T6.3 is the third target of SDG 6).

For OHI, there are ten goals: G1—food provision; G2—artisanal fishing opportunities; G3—natural products; G4—carbon storage; G5—coastal protection; G6—tourism and recreation; G7—coastal livelihoods and economies; G8—sense of place; G9—clean waters; and G10—biodiversity. Furthermore, each goal has specific components (<http://www.oceanhealthindex.org/methodology/goals>). Some components can occur in more than one goal (e.g., nutrient pollution).

The findings show which approach could be followed to assess a specific pressure found in one of the environmental indicators, descriptors, targets, or/and goals. For instance, an environmental engineer working on nutrient enrichment assessments could follow the application made by (D. Wang *et al.*, 2018) and related frameworks (see Table 15).

Table 15: *A review of the remote sensing applications that are being developed for each pressure related to coastal and marine areas.*

Pressures	Sub-Pressures	RS technology	IFSRS Data	Description / Application	Reference	Environ- ment	WFD	MSFD	UN SDG	OHI
		SRS, ARS, UAV, USV, UUV, SS	Satellite			Coastal / Marine	Indicators	Descriptors	Targets	Goals
Nutrient enrichment	General	SRS	GOCI /SMAP	Satellite retrieval of surface water nutrients in coastal region	(D. Wang <i>et al.</i> , 2018)	C/M	BQE	D5	T3.9	G1–10
									T6.3	
Underwater noise	General	ARS	–	Optical remote sensing of sound in the ocean	(Churnside <i>et al.</i> , 2014)	M			T14.1	
		SS	–	Baseline assessment of underwater noise in the Ria Formosa using SS	(Soares <i>et al.</i> , 2019)	C/M		D11	T14.4	
Death and injury	General	SRS	Landsat /MO DIS	Extensive coral mortality and critical habitat loss following dredging and their association with RS of sediment plumes	(Cunning <i>et al.</i> , 2019)	C/M	BQE	D1	T14.4	G1–8
								D3	T14.5	
Presence of Marine Litter	General	–	–	Towards the integrated marine debris observing system (IMOS)	(Maximenko <i>et al.</i> , 2019)	C/M		D6	T12.2	G10
								D10	T14.1	

	Macro plastics on the ocean	ARS	-	Sensing ocean plastics with an airborne hyperspectral shortwave infrared imager	(Garaba <i>et al.</i> , 2018)	M				
			-	Monitoring of beach litter by automatic interpretation of UAV images using the segmentation threshold method	(Bao <i>et al.</i> , 2018)	C				
		UAV	-	Use of UAV for efficient beach litter monitoring using a beta version of a machine learning tool	(Martin <i>et al.</i> , 2018)	C				
	General Marine Litter		-	Anthropogenic marine debris assessment with UAS imagery and deep learning	(Fallati <i>et al.</i> , 2019)	C				G6–10
		SRS	WorldView 3	Anthropogenic marine debris over beaches: Spectral characterization for SRS application	(Acuña-Ruz <i>et al.</i> , 2018)	C/M				
		ARS	-	Mapping coastal marine debris using ARS imagery and spatial analysis	(Moy <i>et al.</i> , 2018)	C/M				
Substratum loss	-	ARS/SRS	WorldView 2	Automating nearshore bathymetry extraction from wave motion in satellite optical imagery	(Mancini <i>et al.</i> , 2012)	M	HQE	D6	T14.4	G1–5 G7–8 G10
Coastal Erosion	General	SRS	(Optical SRS)	Shoreline detection using optical remote sensing: A review	(Toure <i>et al.</i> , 2019)	C		D7	T14.2 T9.1 T11.1 T11.5	G5
Change in Salinity	General	SRS	Landsat 8 OLI	Remotely sensed sea surface salinity in the hyper-saline Arabian Gulf: Application to Landsat 8 OLI data	(Zhao, Temimi and Ghedira, 2017)	C/M	PCQE	D7	T14.1	
		SRS	Aquarius	Assessment of Aquarius sea surface salinity	(Kao <i>et al.</i> , 2018)	C/M				
Introduction of	Hydrocarbons	SRS	-	A review of oil spill remote sensing	(Fingas and Brown, 2017)	C/M	PCQE	D8	T6.3	G1–10

synthetic compounds	UAV		-	Distributed operation of collaborating UAVs for time-sensitive oil spill mapping	(Odonkor, Ball and Chowdhury, 2019)	C /M	PCQE	D5	T14.1	G1–10
									T3.3	
									T3.9	
	Toxic metal	SRS	Landsat	Assessment ecological risk of heavy metal using SRS	(Zhu <i>et al.</i> , 2017)	C				
The input of organic matter	Organic Matter	SRS	Landsat	SRS data from Landsat to estimate organic matter distribution	(X. Wang <i>et al.</i> , 2018; Han <i>et al.</i> , 2019; Zhai, 2019)	C /M	PCQE	D5	T6.3	
	Dissolved Organic Matter (DOM)	SRS	MERIS L1	DOM at the fluvial–marine transition in using in situ data and ocean colour RS	(Juhls <i>et al.</i> , 2019)	C /M			T14.1	
									T3.3	
									T3.9	
			MODI /Aqua	Long-term changes in coloured DOM from SRS data from MODIS	(Xiao <i>et al.</i> , 2018)	M				
Input of radionuclides				RS radiation mapping: overview and application of current and future aerial systems	(Connor, Martin and Scott, 2016)	C	PCQE	D8	T6.3	G9
	General	SRS /ARS	Landsat	Distribution of radioactive black sand along a coastal area using ARS and SRS	(Kaiser, Aziz and Ghieth, 2014)	C			T14.1	
									T3.3	
									T3.9	
	UAV	-	Radiological assessment on interest areas on the Sellafield nuclear site via unmanned aerial vehicle	(Martin <i>et al.</i> , 2016)	C					
Thermal pollution	General	SRS	Landsat	Detection of thermal pollution from power plants on China’s eastern coast using remote sensing data	(Ma <i>et al.</i> , 2017)	C /M	PCQE	D7	T14.1	G2–8 G10
			HJ–1B						T14.3	
			MODIS						T3.3	
									T3.9	

Wiedenmann, 2014; Newton *et al.*, 2014). These pressures affect the function of aquatic ecosystems and lead to the decline of marine habitats. RS monitoring approaches can offer high-frequency and large-scale observation to assess nitrate and phosphate as important water quality indicators. (D. Wang *et al.*, 2018) used SRS images from GOCI and SMAP satellites together with sea surface salinity and remote-sensing reflectance models that enabled them to obtain long time-series variation in nitrate and phosphorus concentration. MODIS, MERIS, Landsat, and SeaWiFS SRS images can be used for short-term detection. Furthermore, (Arteaga, Pahlow and Oschlies, 2015) provided a model derived from satellite-sensed components, such as sea surface temperature, chlorophyll, and others, to estimate a global monthly nitrate concentration at the sea surface.

II.2. Underwater noise

Human activities, such as maritime transport, fishing, geophysical exploration, and dredging, increase the pressure of underwater noise by generating a sound that causes negative impacts on marine life. This pressure can be amplified in shallow water, such as lagoons (Soares *et al.*, 2019; El Mahradi *et al.*, 2020). (Churnside, Naugolnykh and Marchbanks, 2014) suggested theoretical approaches that use ARS images (i.e., LiDAR) to measure sound in the upper ocean by modelling natural bubbles near the sea surface. (Soares *et al.*, 2019) used the RS approach based on SS hydrophone (called digitalHyd SR-1) to record the noise between summer and winter in the Ria Formosa lagoon in Portugal.

II.3. Death and injury

Death and injury pressures on marine organisms can be posed by several activities, such as smothering or dredging materials. (Cunning *et al.*, 2019) used SRS data from MODIS and Landsat images to identify sediment plumes in the port of Miami and to quantify its effect on coral mortality and critical habitat loss. This was combined with *in situ* data to reliably evaluate the magnitude and extent of the area affected by the dredging activity.

II.4. Presence of marine litter

The issue of marine litter, especially marine plastic, has been highly visible on all media types and has focused public concerns on this type of pollution as an important societal problem. Efforts to tackle marine litter have focused on the management aspect, rather than monitoring pressures (Borja and Elliott, 2013, 2019).

There are many types of debris that can be found on the coast and the sea, including microplastics, as well as many other wastes. RS applications to marine litter are still in their early stages, but present a great potential to provide global monitoring with extensive coverage and long-term assessment (Moller, Chao and Maximenko, 2016).

II.4.1. General Marine Litter

Different RS technologies can be applied to assess marine litter from space (SRS, ARS, and UAV). UAVs are the most used, as they are 39 times faster than a visual census (Martin *et al.*, 2018). The segmentation threshold method, using statistical information of image histograms, is considered a suitable approach for extracting targets from UAV images (Bao *et al.*, 2018). (Fallati *et al.*, 2019) combined UAV images with deep-learning-based software to confirm the efficiency of UAVs as tools for monitoring and to demonstrate the potential of deep learning for automatic detection. (Martin *et al.*, 2018) used a beta version of the machine learning tool. Furthermore, ARS and SRS have been used to collect marine litter information. (Moy *et al.*, 2018) used high-resolution SRS imagery for automatic digital classification of marine litter. From an assessment of three beaches, the images were integrated with hyperspectral laboratory measurements that showed an overall accuracy equivalent to 88% with detection of over 50 tons of debris. (Moy *et al.*, 2018) provided precise macro-debris ($>0.05 \text{ m}^2$) measurements to identify 20,658 debris items with their location, type, and size along 1600 km of coastline in the Huawei island by using ARS images; plastics comprised 83% of the total count.

At a regional scale, a beach litter database for the European sea (under the EMODnet initiative) has been developed by the European Commission (JRC), HELCOM, OSPAR, and the MSFD marine litter group by assessing 518 beaches from 29 countries, including SRS surveys (Addamo *et al.*, 2018).

Moreover, (Maximenko *et al.*, 2019) suggested a conceptual model of an Integrated Marine Debris Observing System (IMDOS) to monitor changes and distribution of marine debris dynamics by providing a global coverage and precision by using RS data (SRS, ARS, UAV, USV, and SS) and *in situ* data in order to mitigate the impacts effectively.

II.4.2. Marine Plastic

The plastics eventually accumulate in the five ocean gyres, forming garbage patches that are so large that they are visible from space. The plastic particles can be detected through RS images. (Garaba *et al.*, 2018) used ARS hyperspectral shortwave infrared images to separate marine litter from surrounding seawater using the unique absorption features of the polymer

identification technique. (Goddijn-Murphy *et al.*, 2018) presented a concept of the spectral model of a hyperspectral RS algorithm that calculates sea surface plastic litter and concluded that it could be visible with spectral light reflectance measurements. A comprehensive SWIR (Short Wave Infrared) spectral signature library for oceanic plastics is in progress.

II.5. Substratum loss

Substratum is important for benthic and demersal species that live associated with the bottom habitat, and sea-floor integrity is a descriptor of marine environmental status (D6 of MSFD). RS can assess the substrates, especially in shallow water. An indirect method to evaluate the bottom is to assess the evolution of water depth. (Mancini *et al.*, 2012) compared ARS data using Lidar with SRS data derived from Worldview2 to analyse the sea depth and demonstrated a low relative error between both datasets.

II.6. Coastal erosion

Anthropogenic activities, such as the use of sand for urbanization, dredging, and building coastal infrastructure, may lead to coastal erosion pressures and the displacement of the shoreline by natural forces from waves and currents. (Toure *et al.*, 2019) presented a state-of-the-art review on the image processing methods using optical SRS for shoreline detection. This includes a summary of shoreline indicators, a list of segmentation, and edge detection approaches.

II.7. Change in salinity

Salinity can change due to natural and/or human factors, and RS can be used to assess these changes. Satellite colour imagery (SRS) can be used to measure salinity.

Soil Moisture and Ocean Salinity (SMOS) was the first mission to measure global Sea Surface Salinity (SSS) from space and which started in 2009. Then, it was followed by the Aquarius mission in 2011, which experienced a power failure and stopped working in 2015. The measurement of SSS has been further enhanced after the launch of the Soil Moisture Active–Passive (SMAP) mission in 2015 that provided improved spatial and temporal resolutions compared to previous methods (S. Bao *et al.*, 2019). However, all these missions presents large discrepancies that can be found in high latitudes and in the regions along the coast (S. Bao *et al.*, 2019).

Furthermore, different alternatives were developed to improve the salinity data products. For instance, algorithms were used to convert data from the absorption of coloured dissolved organic matter that can be retrieved into salinity units (Fingas, 2019b).

Statistical approaches, such as multi-linear regression, neural networks, least square regression, and the Box–Jenkins algorithm (Zhao, Temimi and Ghedira, 2017), can also be used to measure radiance or reflectance correlated with salinity. (Zhao, Temimi and Ghedira, 2017) used SRS from Landsat 8 OLI data to assess sea surface salinity in the hyper-saline Arabian Gulf while (Kao *et al.*, 2018) used the SRS image from Aquarius satellite data to measure the salinity.

II.8. Input of non-synthetic compounds: hydrocarbons

Increased activities on the coast and at sea, such as offshore oil and gas platforms, transport and shipping, as well as urban runoff, have increased the risk of pollution and contamination from synthetic compounds, hydrocarbons (oil and gas), and metals. RS data have played an important role in assessing oil spills, which are a major environmental concern that can have dramatic consequences (Fingas and Brown, 2014; Alpers, Holt and Zeng, 2017; Bayramov, Bayramov and Aliyeva, 2018).

SAR (SRS) data can be used to detect oil spills; nevertheless, they are limited in their capacity to separate mineral oil from natural, biogenic films (Alpers, Holt and Zeng, 2017), because of noise in the signal. Moreover, there are challenges due to the oil slick thickness that have been poorly studied (Fingas, 2018). A review of oil spill remote sensing is presented by (Fingas and Brown, 2017) where radar (SRS) is the dominant approach for mapping oil spills. (Odonkor, Ball and Chowdhury, 2019) established a distributed approach (called PSOil) to map offshore oil spills using a collaborating team of UAVs.

II.9. Input of non-synthetic compounds: toxic metals

Human activities from industries, agriculture, transport and ports, as well as sewage effluent increase the pressure of metal contamination and pollution on the coastal and marine environment. Metals are non-biodegradable and some are toxic, as well as accumulating in sediments and biota, presenting a serious environmental problem (Sharifuzzaman *et al.*, 2016). (Zhu *et al.*, 2017) used SRS data from Landsat images to assess the risk of heavy metals in a coastal area that was affected by high-intensity land reclamation.

II.10. Input of organic matter

Anthropogenic activities, such as the input of sewage effluent and manure, paper mills, and food processing, increase the pressure of organic matter inputs into coastal and marine ecosystems, and can result in reduced water quality and ecosystem health (Deininger and Frigstad, 2019). Organic matter can be either particulate (POM) or dissolved (DOM). DOM can also come from natural processes, such as fluvic and humic acids. Once in the aquatic system, it becomes a dissolved organic matter (Findlay and Parr, 2017). Therefore, the Coloured Dissolved Organic Matter (CDOM), which is an optically active subset of DOM, is considered as an important tracer of effluent plumes in coastal waters (Nezlin *et al.*, 2020). (Aurin and Dierssen, 2012) presented limitations and advantages of ocean colour RS for detecting the CDOM.

RS images have been deployed in many research studies to estimate the organic matter in coastal and marine environments. (X. Wang *et al.*, 2018; Han *et al.*, 2019; Zhai, 2019) used SRS data from Landsat images using different approaches to estimate soil organic matter for different coastal ecosystems. (Juhls *et al.*, 2019) used SRS data from MERIS L1 satellite scenes to test the statistical performance of five ocean colour remote sensing algorithms and to evaluate the credibility of the spatial distribution of the derived DOM at a fluvial–marine transition area. (Cao *et al.*, 2018) used new RS algorithms with a multiple linear regression approach that was developed for retrieving CDOM quality across an estuary ecosystem and that were developed from MERIS/MODIS data.

Long-term changes in CDOM have been presented by (Xiao *et al.*, 2018) using (MODIS)/Aqua products to understand the biogeochemical properties of water bodies and their dynamics.

II.11. Input of radionuclides

Radionuclides (e.g., ^{238}U , ^{232}Th , and ^{40}K) naturally occur on the coast and at sea due to geological processes. Examples are the black sand beaches of Kerela (India) and estuaries in uranium-rich catchments, e.g., Figueira da Foz, Portugal. Anthropogenic activities, such as inputs from a nuclear power plant, can further contaminate sediments (Uddin and Behbehani, 2018), sometimes over long distances, such as atmospheric deposition from Chernobyl on West European systems.

An overview of current and future aerial system applications to map radiation is discussed by (Connor, Martin and Scott, 2016). A gamma-ray spectrometer is generally used to detect, identify, and classify radionuclides (El-Saharty, 2013) and to identify the sources. Gamma-ray

spectrometers can be used on RS devices, such as ARS, UAV, or SRS. (Kaiser, Aziz and Ghieth, 2014) used ARS gamma-ray spectrometry and SRS from Landsat to measure radioactive abundance along the Rosetta coast (Egypt). They found high concentrations of potassium and a high relative abundance of uranium and thorium due to fertilizer application on cultivated land in the Nile Delta. (Martin *et al.*, 2016) deployed a lightweight radiation detection system on a UAV to measure the distribution of radiation with a high accuracy, spatial resolution, and sensitivity for the assessment of a nuclear site in England.

II.12. Thermal pollution

Power plant activities discharge cooling water, causing thermal pollution pressure on the coastal waters that can be assessed by measuring the water temperature distribution (Chen, Shi and Mao, 2003). This is difficult and expensive through *in situ* measurement, making RS technologies an excellent tool for this purpose.

(Ma *et al.*, 2017) used a combination of SRS data from Landsat (ETM+), HJ-1B, and Terra (MODIS) satellites to compare sea surface temperature before and after an operating nuclear power plant in the coastal area of China and detected a rise of more than 3 °C at approximately 17 km.

III. RS and state changes

The pressures from human activities cause state changes in the environment, especially the physio-chemical variables and biological quality elements (Newton *et al.*, 2014; Elliott *et al.*, 2017). These are also relevant to several environmental policies, such as the WFD and the MSFD. These variables will be described one by one in this section.

Recent advances in RS technologies can quantify and assess the environmental state changes. Table 16 summarizes the recent advanced application of RS in relation to the state changes on the environment that can be found in marine and coastal systems.

III.1. Water quality

Combining *in situ* and RS data for water-quality monitoring allows a holistic analysis that can provide alternative management scenarios (Markogianni *et al.*, 2018). Coastal and ocean monitoring are challenging due to multiple sources that modify physico-biological processes (Pahlevan and Schott, 2013). (Gholizadeh, Melesse and Reddi, 2016) presented a review of the commonly employed SRS and ARS to investigate and identify eleven water-quality parameters. A list of sensors for water assessment was presented, including a scan system, type,

resolution, spectral range, number of bands, and imaging swath. Furthermore, a list of spectral bands combination and their ratios to assess some parameters is presented as well.

(Chang, Imen and Vannah, 2015) presented state-of-the-art technology of RS platforms and their sensors that are used for monitoring water quality status and ecosystem state in relation to the nutrient cycle.

Table 16: A review of the remote sensing applications that are being developed for each state change related to coastal and marine areas.

State changes	Sub-State changes	RS technology	If SRS Data	Description / Application	Reference	Environ ment	WFD	MSFD	UN SDG	OHI
		SRS, ARS, UAV, USV, UUV, SS	Satellite			Coastal Marine	Indicators	Descriptors	Targets	Goals
Water quality	General	SRS	-	A comprehensive review on water quality parameters estimation using RS techniques	(Gholizade et al., 2016)	C/M	PCQE		T3.3	
		ARS							T3.9	
								D1	T6.1	
								D5	T6.3	G1–10
								D7	T14.1	
								D8	T3.3	
									T3.9	
Water turbidity		SRS	GOCI	GOCI, the world's first geostationary ocean colour observation satellite, for the monitoring of temporal variability in coastal water turbidity	(Choi et al., 2012)	C/M	PCQE	D7	T6.3	G9
									T14.1	
Suspended particulate matter		SRS	GOCI	Using GOCI data to map the diurnal dynamics of suspended particulate matter in coastal waters	(He et al., 2013)	C/M	PCQE	D8	T6.3	G9
									T14.1	
Marine Habitat (Flora)	General	SRS	-	A review of RS approaches for monitoring blue carbon ecosystems: mangroves, seagrasses and salt marshes	(Pham et al., 2019)	C/M	BQE	D1	T14.2	G1–5
		ARS							T14.2	G7–8
		UAV							T15.1	G10
		USV								
	General	UUV	-	Monitoring marine habitats with photogrammetry: a cost-	(Marre et al., 2019)	M			T15.5	

				effective, accurate, precise, and high-resolution reconstruction method						T15.7							
										T12.2							
	Wetlands	SRS	-	A review of wetland RS	(Guo <i>et al.</i> , 2017)	C	BQE										
		ARS															
	Mangrove	SRS	-	A review of RS for mangrove forests: 1956–2018	(Wang <i>et al.</i> , 2019)	C											
		ARS															
		UAV															
Seagrass	SRS/ARS	-	Mapping, monitoring, and modelling seagrass using RS techniques	(Phinn <i>et al.</i> , 2018)	C/M												
	UAV/USV																
	UUV/SS																
Coral reefs	SRS	-	RS of coral reefs for monitoring and management: a review	(Hedley <i>et al.</i> , 2016)	C/M												
	ARS																
Vegetation changes	SRS	Landsat	Checking vegetation changes with SRS: The case of the Trieste province (Italy)	(Favretto, 2018)	C												
Marine Habitat (Fauna)	General	UAV	-	A review of unmanned vehicles for the detection and monitoring of marine fauna	(Verfuss <i>et al.</i> , 2019)	M						D1	T14.4	G1–5			
		USV															
		UUV															
	Sea birds and Mammals	ARS	-	Monitoring seabirds and marine mammals by georeferenced aerial photography using ARS	(Kemper <i>et al.</i> , 2016)	M									D4	T15.5	G7–8 G10
	Turtles	UUV with SRS	-	Seasonal movements of immature Kemp’s Ridley sea turtles (<i>Lepidochelys kempii</i>) using UUV	(Coleman <i>et al.</i> , 2017)	M											
Sharks	SRS	-	SRS in shark and ray ecology, conservation and management	(Williamson <i>et al.</i> , 2019)	M						T12.2						
Benthic environment		UUV	-	Predicting the distribution of deep-sea vulnerable marine ecosystems using high-resolution data	(Rengstorf <i>et al.</i> , 2014)	M					BQE	D1	T14.4	G1–5			
															D6	T15.5	G7–8 G10

Physical parameters changes	Sea surface temperature	SRS	-	Half a century of SRS of sea-surface temperature	(Minnett <i>et al.</i> , 2019)	C/M	PCQE	D7	G2–5	
	High wave exposure	SRS	(Radar)	Significant wave height measured by coherent x-band radar SRS	(Carrasco, Horstmann and Seemann, 2017)	M	HQE		T14.1	G7–8 G10
Coastal landslides		SRS	ENVISAT	The combined use of PSInSAR and UAV photogrammetry techniques for the analysis of the kinematics of a coastal landslide affecting an urban area (SE Spain)	(Mateos <i>et al.</i> , 2017)	C			T15.3	(only if they are related to sea-level rise)
		UAV							T11.1	
Land subsidence		SRS	(Mainly) Sentinel-1	SRS for monitoring land subsidence of coastal cities in Africa	(Cian, Blasco and Carrera, 2019)	C		D7	T11.5	
									T15.3	
Shoreline evolution		SRS	Landsat Gaofen-1 (WV)	Shoreline evolution in an embayed beach adjacent to tidal inlet: Using SRS	(R. Zhang <i>et al.</i> , 2019)	C		D7	T13.1	G5
									T11.1	
Turbidity plumes		SRS	Landsat MODIS	Detection of turbidity plumes and artificial islands using RS data	(Barnes and Hu, 2016)	C/M	PCQE	D7	T11.5	
									T6.1	G9
Harmful Algal Bloom	General	SRS	CZCS, SeaWiFS, MODIS MERIS	A review of ocean colour RS methods and statistical techniques for the detection, mapping, and analysis of phytoplankton blooms in coastal and open oceans	(Blondeau-Patissier <i>et al.</i> , 2014)	C/M	BQE	D5	T3.9	G1, G2, G3, G4, G5, G6, G7, G8, G9, G10
									T6.1	
pH changes	General	SRS	-	RS of surface ocean PH exploiting sea surface salinity satellite observations	(Sabia <i>et al.</i> , 2015)	M	PCQE		T6.3	
									T14.1	
									T14.3	

III.2. Water turbidity

RS images can be used for understanding the temporal turbidity changes and sediment dynamics in coastal systems. (Choi *et al.*, 2012) showed the effectiveness of using RS data from the Geostationary Ocean Colour Imager (GOCI) for monitoring the temporal dynamics of coastal water turbidity.

III.3. Suspended particulate matter

In coastal waters, geostationary satellite ocean colour daily data is used to map the dynamics of suspended particulate matter. SRS image from GOCI provides hourly observations that can successfully map SPM in different areas, even in highly dynamic coastal waters (He *et al.*, 2013). (Shang and Xu, 2018) used the atmospheric correction algorithm (UV-AC) from GOCI images, a method developed by (He *et al.*, 2013) and it has been validated with *in situ* data that showed its potential in coastal turbidity waters.

III.4. Coastal and marine habitats

There are different types of coastal and marine habitats, such as wetlands, coastal vegetation, salt marshes, mangroves, seagrasses, coral reefs, and kelp beds, that provide a range of valuable goods and services to the environment and humans. The mapping of coastal and marine habitats is a preliminary step for studies of ecosystems. (Pham *et al.*, 2019) presented a comprehensive review of RS data used for mapping and monitoring blue carbon ecosystems (mangroves, seagrasses, and salt marshes), including high spatial resolution and medium/low spatial resolution with different sensors from SRS, ARS, UAV, and USV. The review covers studies undertaken from 2010 to 2018. Furthermore, (Marre *et al.*, 2019) developed a cost-effective UUV, using a photogrammetry approach that can produce accurate and precise high-resolution models to monitor marine habitats on a small scale (e.g., biogenic reefs and seagrass meadows).

III.4.1. Wetlands

Coastal wetlands play an important role in protecting communities from climate change impacts, as they moderate the climate and at the same time, are vulnerable ecosystems (Moomaw *et al.*, 2018; Newton *et al.*, 2020). RS applications provide knowledge to understand the functioning process of these ecosystems. (Guo *et al.*, 2017) provided an overview of the application of SRS and ARS data to wetland research by reviewing seven types of sensors. These include aerial photos with coarse-resolution, medium-resolution, high-resolution, hyperspectral imagery, radar, and LiDAR data to track the changes in wetland ecosystems.

III.4.2. Mangrove Change

Mangroves are highly productive ecosystems on tropical coasts. Their changing state can impact the entire surrounding ecosystems. RS applications for mangroves include distribution, biophysical parameter identification, and characterization of their state. (Wang *et al.*, 2019) highlighted the major RS development for mangroves by reviewing historical research from 1956 to 2018. This includes SRS, ARS, and UAV uses for understanding and analysing these ecosystems. Furthermore, different aspects were reviewed, including extent (area) mapping, leaf area index estimation, species classification, height estimation, carbon stock estimation, health assessment, carbon flux characterization, ecohydrology, and climate impact on mangroves.

III.4.3. Seagrass

Seagrasses are foundation species for physio-chemical and biological processes in coastal and marine ecosystems (Thorhaug *et al.*, 2015). They also provide habitat for other organisms, such as juvenile fish and invertebrates. Numerous studies have documented the advantages of RS technologies for seagrass research: SRS (Bakirman, Gumusay and Tuney, 2016; Elso *et al.*, 2017), ARS (Hill *et al.*, 2014), UAV (Duffy *et al.*, 2018) to USV, and SS (Gumusay *et al.*, 2019). To assess the state change of seagrasses, (Phinn *et al.*, 2018) presented an overview of the RS platforms that can be used to assess state changes, measure biophysical properties, map, monitor, and model the seagrasses ecosystem, as well as specifying the environmental conditions that do not allow the RS and their approaches to work.

III.4.4. Coral Reefs

Coral reef communities are facing state changes and are even in decline worldwide due to natural and anthropogenic pressures from different activities at the local, regional, and global scales (Xu and Zhao, 2014; Wenger *et al.*, 2016). To assess and measure the effects of such pressures in complex coastal and marine ecosystems, RS are becoming keystone technologies to tackle this crisis and that can be deployed as well to quantify their distribution and their changes (Purkis, 2018). (Hedley *et al.*, 2016) presented a full review of RS technologies that can be applied to monitor and manage changes in coral reefs ecosystems, including SRS and ARS.

III.4.5. Macroalgae

High-Resolution SRS Observations have been used as well to detect *Sargassum* blooms (Xing *et al.*, 2017). In general, these macroalgae can grow so large that they blanket coastlines or can cover large areas of the sea, such as the case of green tides that occurred for eleven consecutive years in the Yellow Sea (J. Zhang *et al.*, 2019).

III.4.6. Vegetation Change

Coastal vegetation is effective for protecting coastal cities from sea storms and, also, from erosion on the watershed and their rivers. Their changes might impact the ecosystems, such as a change in sedimentation flux, water flux, and biodiversity changes. (Favretto, 2018) applied a change detection analysis to the thematic map time series by SRS from Landsat to assess the forest vegetation changes in the Trieste province of Italy through the use of an Enhanced Vegetation Index (EVI) as a suitable index for their physical characteristics.

III.5. Marine fauna

Marine fauna provides a variety of ecosystem services for nature and humans, such as food (provisioning service) and cetacean watching (cultural service). However, human activities and resulting pressures degrade the health and sustainability of marine fauna. RS technologies have been used for tracking marine fauna to monitor and assess changes in their status. Satellite telemetry has been used for marine animal surveys to follow a target and track movement.

Recently, UAVs, USVs, and UUVs have provided many new advantages to detect and monitor marine fauna and their state change. There have been improvements in mission safety and repeatability, longer survey durations, and reducing costs. (Verfuss *et al.*, 2019) highlighted suitable systems for three monitoring systems of marine fauna, including population, mitigation, and focal animal monitoring.

III.5.1. Sea Birds and Marine Mammals

Sea birds and marine mammals include important “top predator” species of the marine ecosystem. RS technologies have been increasingly used for research on seabirds and mammals in recent years. (Kemper, Weidauer and Coppack, 2016) used the ARS approach to detect and identify marine mammal species or a species group using a twin-camera system that generates high-quality images. This approach can be applied to complement land-based species counts.

III.5.2. Turtles

Satellite telemetry has been used to track the movement of turtles and changes. (Coleman *et al.*, 2017) used a UUV attached to the back of sea turtles (called Platform Terminal Transmitter PPT) that is tracked with earth-orbiting satellite to follow the movement of turtles. The collected data showed changes that happened in the Mississippi-Gulf region.

III.5.3. Sharks

Sharks are also important apex predator species of the marine ecosystem. Their populations have been declining during the last five decades, with resulting state change in many marine ecosystems (Heupel *et al.*, 2014). SRS has been used in many research studies to follow the activities and pressures, causing the decline of sharks. (Williamson *et al.*, 2019) presented a global map that shows the regions where SRS has been deployed for shark ecology and conservation, showing a common tagging technology.

III.5.4. Benthic environment

Activities and pressures to the marine environment affect the spatial distribution of benthic species in both shallow waters and the deep sea, which contributes to the state change of these benthic ecosystems. (Rengstorf *et al.*, 2014) provided an overview of methodologies used to predict the distribution of deep-sea benthic species. The Irish remotely-operated vehicle (ROV) Holland I and a UUV were deployed to assess the benthos by using high-resolution imagery. This enabled the assessment of changes and illustrated the emerging issues.

III.6. Physical parameter changes

The physical parameters of seawater can be measured directly and indirectly. Direct *in situ* measurements can be expensive to carry out in the field. RS applications are often the most cost-effective and fit for purpose options to assess these parameters and changes that affect the environmental state of the coastal and marine ecosystems. Some of the important physical parameters are sea surface temperature (SST), sea currents, and waves.

III.6.1. Sea Surface Temperature (SST)

SST is the most important physical parameter to be measured to monitor the state change and the health of the coastal and marine environments. Several anthropogenic activities and pressures can affect SST, and most of the marine ecosystems can be affected. Examples of this are widespread coral bleaching events. SRS data provides a comprehensive view of the coastal and marine ecosystems and allows a synoptic measurement of SST, which has been used in

research worldwide (Njoku, 1990; Azmi *et al.*, 2015; Waga *et al.*, 2017; Robles-Tamayo *et al.*, 2018). (Minnett *et al.*, 2019) provided a half-century of the historical development of SRS sensors to measure SST. The challenges of data volumes, distribution, analysis, and communication are included.

III.6.2. High Wave Exposure

The measurement of wave height and storm surge is essential for coastal protection, shipping, and offshore operations. Anthropogenic activities and pressures can increase the vulnerability to natural hazards, for example, by urbanizing low-lying coasts. Low-lying coastal urban areas and atolls are key societal hotspots of coastal vulnerability and changes in wave exposure (Nicholls *et al.*, 2014). Radar images have been the most significant sensors used to assess changes in wave and to estimate wave height (Carrasco, Horstmann and Seemann, 2017; Kammerer and Hackett, 2017; Liu, Huang and Gill, 2017). SRS contributes to increasing operational awareness and human safety and many marine applications.

III.7. Coastal landslide

Landslides have impacted coastal structures, cliffs, and hillsides in many regions around the world. These are associated with an increase of severe weather events associated with climate change (Leshchinsky *et al.*, 2017). They are also related to urbanization activities and pressures (Li *et al.*, 2017). The most extreme coastal landslide example known in the Mediterranean coast (Cármenes del Mar resort, Granada, Spain) was assessed by deploying SRS using ENVISAT SAR images and a UAV using the photogrammetry approach, and both applications allowed quantifying the changes of building displacements and the structural changes as well (Mateos *et al.*, 2017).

III.8. Land subsidence

Growing urbanization in major coastal cities has led to various activities and pressures, such as overexploiting groundwater, reclaiming lands, and built-up areas (Sekovski, Newton and Dennison, 2012). These result in a state change on the coastal environment causing surface deformation and land subsidence, especially in river-mouth systems (Syvitski *et al.*, 2009). RS can be deployed to identify the areas most vulnerable to land subsidence. (Cian, Blasco and Carrera, 2019) used SAR data from SRS Sentinel-1 images and applied Persistent Scatterer Interferometry (PSI) technique as a powerful tool able to monitor displacements of the Earth's surface over time (Crosetto *et al.*, 2016). The research integrated the Sentinel Application Platform (SNAP) and the Stanford Method for Persistent Scatterers (StaMPS), which showed

the potential to monitor land subsidence and coastal resilience assessment in many African coastal cities.

III.9. Shoreline changes

Coastal erosion pressures usually lead to beach and shoreline changes due to different anthropogenic activities. Historical RS data can document the evolution of coastal shorelines and their changes. (R. Zhang *et al.*, 2019) used SRS from Landsat and Gaofen-1 (WFV) satellites to extract shoreline data and their evolution for 20 years, to detect the state changes of Wenchang City beach, in South China.

III.10. Turbidity plumes

Turbidity plumes are mostly produced during dredging and drilling activities and cause a state change in the marine environment. They can be detected through RS images. For instance, building an artificial island in the South China sea has led to turbidity plumes that were detected through SRS using Landsat and MODIS data (Barnes and Hu, 2016). A turbidity index was developed as a simple subtraction algorithm difference between two Rayleigh-corrected reflectances at 469 and 645 nm (Feng *et al.*, 2018), which allowed for easy detection of turbidity plumes (Barnes and Hu, 2016).

III.11. Harmful algal blooms

Algal blooms are considered a major indicator of marine ecosystem health, which shows the state change of the environment. Hence, a variety of operational RS sensors have been developed to assess the HAB during the last four decades (Anderson, 2009; Costa Goela *et al.*, 2013; Zhao, Temimi and Ghedira, 2015). Progress and limitations of the developed algorithms used through multispectral ocean colour SRS sensors, such as CZCS, SeaWiFS, MODIS, and MERIS, have been discussed and reviewed by (Blondeau-Patissier *et al.*, 2014) in order to understand the triggering factors behind algal blooms and to analyse their spatio-temporal patterns in coastal and open-sea ecosystems.

III.12. pH changes

Ocean pH is an important environmental variable to assess coastal and marine health ecosystems. Ocean acidification is a decrease in pH that causes a major state change on marine organisms and environments. The surface ocean pH has been estimated through RS application in many ocean regions. (Sabia *et al.*, 2015) presented the best appropriate approach to estimate

surface ocean pH through the combination of different existing SRS datasets to unify the fragmented RS study and to generate a novel value-added SRS product.

IV. RS and impact (on welfare)

Changes in the environment that have consequences for societal welfare (goods and benefits) are considered as an impact (on human welfare) (Elliott *et al.*, 2017). At present, only the impacts presenting risk to public health (e.g., gas emission) and risk to public life and infrastructure (e.g., storm surge) can be assessed using RS technologies. Other economic and social impacts (e.g., loss of jobs, loss of revenue) are assessed differently. Table 17 summarizes the recent advanced application of RS in relation to the main impact (on welfare).

Table 17: *The remote sensing applications that are being developed for each impact (on welfare).*

Impact (on Welfare)	Sub-Impact (on Welfare)	RS technology	If SRS Data	Description /Application	Reference
		SRS, ARS, UAV, USV, UUV, SS	Satellite		
Public health risk	Gas Emission	UAV	-	Towards the development of a low-cost airborne sensing system to monitor dust particles after blasting at open-pit mine sites	(Alvarado <i>et al.</i> , 2016)
Risk to public life and infrastructures	Storm surge	SRS	MODIS	Global mapping of storm surges and the assessment of coastal vulnerability	(Brakenridge <i>et al.</i> , 2013)

IV.1. Public health risk

Public health risks impact human health through disease or infectious environmental conditions. Industrial waste gas emission represents a better case for impacting human health and health care expenditure (X. Xu *et al.*, 2019). As air quality monitoring methods use a limited number of fixed sampling, RS technologies that cover a larger area can help to assess the gas emission and dispersion that can affect human health. (Neumann *et al.*, 2013) developed a bio-inspired and particle filter-based algorithm to localize a gas emission and its source using a micro-drone as a UAV. A list of RS technologies that were used for monitoring gases is presented by (Alvarado *et al.*, 2016).

IV.2. Risk to public life and infrastructures

Storm surges pose some of the most devastating hazards to coastal regions that represent a risk to human life and/or an impact on its welfare, as they are both deadly and costly (Patricola and Wehner, 2018; Zhang *et al.*, 2018). RS applications are effective for impact assessment and

future prediction, while ground surveys to assess a post-surge impact are expensive, laborious, and lack a spatial dimension. (Brakenridge *et al.*, 2013) surveyed an SRS application for three catastrophic storm surges worldwide and presented a global mapping approach to assess coastal impact and vulnerability.

V. RS as a response (as a measure)

Coastal and marine responses are measures to be taken to face changes resulting from drivers, activities, and pressures. Besides the strengths that RS technologies have had on the first DAPSI(W)R(M) component, “D-A-P-S-I(W)”, the application of these technologies can be a major response (as measure) in emerging and developing economies countries by building a collaborative unit and practical framework that will integrate all sectors that can use RS in order to assess and monitor drivers, activities, pressures, and state change on their coastal and marine environment.

The measures should follow the 10-tenets approach for adaptive management and sustainability, developed by (Barnard and Elliott, 2015).

Ecological RS applications with the different sensors have proven to be useful, such as the monitoring of blue carbon ecosystems (Butt *et al.*, 2019; Pham *et al.*, 2019), habitat (Warren *et al.*, 2016), and valuation of ecosystem services (de Araujo Barbosa, Atkinson and Dearing, 2015; Vaz *et al.*, 2019). For instance, coral reef restoration as a measure could be addressed by using RS technologies as they provide information on various abiotic conditions and other site characteristics (Foo and Asner, 2019).

Another essential response (as a measure) is to use low cost SS to obtain and communicate significant parameters to monitor the coastal and marine environment. (Lay-Ekuakille *et al.*, 2019) presented the advances in SS that could help to monitor water quality.

To manage natural resources and protect the coastal and marine ecosystems in conflict zones, RS can be used to access politically sensitive areas (Levin *et al.*, 2019).

Civil security and public safety due to natural hazard (e.g., floods and hurricanes) and/or anthropogenic disaster (e.g., industrial waste gas emission and broken dams) that may occur in coastal and marine areas could be assessed using RS technologies. For instance, UAVs have shown great potential in their application as a response to the disaster (Hildmann and Kovacs, 2019).

VI. DISCUSSION

RS technologies present an opportunity to assess and analyse important elements of the DAPSI(W)R(M) framework. Despite their strengths, the advances in RS sensors still have limitations and offer challenges to enable a holistic coastal and marine management application. Therefore, there are still large improvements to be made to achieve environmental integration for assessment and monitoring. Challenges facing current sensors for future uses, opportunities, and recommendations to move toward integrated management, as well as recommendations to overcome the challenges, are presented in the following sections (Sections VI.1 – VI.2).

VI.1. Limitations of current technologies and challenges

There are some limitations to existing RS technologies and challenges for their application that should be addressed to implement integrated coastal and marine environmental management. Current RS technology is still not developed enough to monitor complicated ecosystems, presenting deficiencies in many aspects, such as sensors, used technologies, data collection, storage, uncertainties, extrapolation, affordability, accessibility, dissemination, communication, and political issues.

VI.1.1. Technology-based challenges

The challenges here consider the RS technologies reviewed under this research: SRS, ARS, UAV, USV, UUV, and SS.

SRS Challenges: Despite the wide-ranging observation of coastal and marine ecosystems over a large spatio-temporal scale through SRS, satellite data still offer challenges. Their resolutions are generally coarser compared to other sensors related to the assessment of specific target activities (e.g., livestock and aquaculture), pressures (e.g., underwater noise and presence of marine litter), and state changes (e.g., marine habitat). Most of the SRS-based research has so far been focused on a few aspects related to coastal and marine environments. Past datasets derived from previous SRS missions are limited by the coarse resolution to perform time series analysis and predict future state changes and impacts. Some SRS sensors present significant uncertainties for the detection of variables: for instance, due to noise, oil spill pressure detection is limited when using spaceborne polarimetric SARs (Alpers, Holt and Zeng, 2017).

ARS challenges: ARS images still need improvement for flight pathways with georeferenced lines (Pepe, Fregonese and Scaioni, 2018). The resulting images need to be processed in

standardized ways to match with other sensors. ARS missions remain expensive compared to other sensors.

Due to wide flight lines along coastal and marine environments, the collected data could be ambiguous for some specific targets.

UAV challenges: UAV missions are often carried out by private research teams, private companies, individual institutions, or individuals. The data are not free and can be costly as well. Despite technological advances with rechargeable batteries, a limited flight duration, mostly less than an hour (mostly small UAV), hampers the ability to cover larger areas and time of the mission; thus, reduced autonomy is challenging (Boukoberine, Zhou and Benbouzid, 2019). While aircraft UAV is capable of reaching altitudes above 12 km (Watts, Ambrosia and Hinkley, 2012), small UAVs still have limited altitude. Limitations to available weight capacity reduce the availability of sensors that can assess specific coastal and marine components, especially for a small UAV (Tahir *et al.*, 2019). Operational safety for UAV missions remains challenging. Attaining extended distances at sea from a coastal mission still needs improvement. A limited flying attitude may disturb wildlife (Fettermann *et al.*, 2019). Finally, coordinating several UAVs during surveillance and pursuit also remains challenging (Las Fargeas, Kabamba and Girard, 2015).

USV challenges: Automated and reliable guidance and navigation for USV remains challenging; also, USV sensing faces limitations from water reflections and visual noises. Hydrodynamic forces and moments are still not fully understood to perform a stable USV mission (Liu *et al.*, 2016). Surveys under extreme weather conditions to assess long-term impacts also remain challenging (Jorge *et al.*, 2019).

UUV challenges: Many factors make the underwater environment challenging, such as the lack of GPS information on positioning the UUV and its sensors, impact of light refraction on reducing field view, as well as underwater clarity and turbidity that could affect the image quality (Guo *et al.*, 2016; Bryson *et al.*, 2017; Marre *et al.*, 2019). UUV's potential risks for disturbing animals is also a challenging task. Avoiding collision between multiple UUVs surveys within their path planning in the complicated marine environments is challenging (Zhuang *et al.*, 2019).

SS limitations: Limited coverage and limited expansion are the challenging gaps that exist on the SS application to derive *in situ* observations. The SS network's communication between different devices remains challenging.

VI.1.2. Uncertainties

RS-derived images are subject to large uncertainties due to the ecosystem complexity of the coastal and marine environments. For instance, coastal shallow water has a high reflectance, which contributes to ambiguity for data acquisition (Zheng and DiGiacomo, 2017). Furthermore, the accumulation of uncertainties at various levels of satellite data processing could generate inaccurate results and interpretation. Therefore, associating uncertainties to a specific variable when assessing coastal and marine parameters is a challenging task. In general, the uncertainty aspect should be revisited in greater detail for each applied method and thus for each parameter.

VI.1.3. Accessibility and affordability

Over the last decades, there have been many applications of RS technologies to assess coastal and marine ecosystems. Many satellites have been launched, and many sensors have been developed due to environmental concerns. However, most of the advances have been centred on the use of data, including acquisition, processing, storing, manipulating, and integrating. There have been significant improvements in the understanding and analysis of environmental issues at the local, regional, and global scale. Nevertheless, accessibility and affordability of RS data is still a challenging issue, especially in countries with limited economic resources.

What are the most pressing challenges? Growing volumes of new high-resolution images are creating challenges for data access. It is costly to build infrastructure, tools, and platforms to access data, and many products are still costly. Capacity building and training of human resources are also costly. UAV, USV, ARS, and UAV data are often still held in private use by research teams, institutions, or private industries, which make access to their data complicated and/or costly.

VI.1.4. Data storage, integration, communication and dissemination

RS data collection is improving, but what are the remaining challenges? There are challenges in regulating effective data storage frameworks and creating standardized protocols for archiving data with emphasis on the marine application. Integrating different data from different RS sources is challenging due to a lack of cooperation between different data holders and a lack of homogeneous protocols. Communication between data holders and data users is also challenging. The coastal and marine research community faces challenges in the dissemination of data and uptake of results to develop integrated coastal marine management.

VI.1.5. Policies and legal issues

At global scales, countries performing SRS missions that can legally collect environmental data could make this data available to other countries. This is a political and ethical issue that has yet to be addressed. RS technologies should be considered as a tool to support integrated coastal and marine management frameworks that are aiming to achieve a healthy environment.

As marine areas are shared between countries, international collaboration is essential to ensure the use of collaborative information from RS technologies. However, an open exchange of RS data is often still challenging. Political issues still create barriers to the free dissemination of data, even for environmental purposes. Regulations regarding the use of UAV, USV, and SS for scientific purposes are still challenging for the scientific community in countries where complicated permissions are required.

VI.1.6. Fragmented expertise and institutions

There is growing knowledge and appreciation of RS applications. Expertise on the use of these technologies for coastal and marine management is still fragmented or siloed. Expertise regarding coastal ecosystems (e.g., lagoons, estuary, and deltas), marine ecosystems (e.g., operational oceanography, offshore energy, and marine habitat) and remote sensing technologies are often separate; for instance, coastal or marine experts might not have an understanding of RS applications and vice versa. Furthermore, RS users might not be knowledgeable about processing RS data. Similarly, institutional specialization can constrain coordination and data transfer, which represents a challenge for knowledge sharing and integrated assessment.

VI.2. Opportunities for improving the integrated coastal and marine environmental management framework

Despite the challenges, there are substantial opportunities to use RS for a further understanding of water and coastal ecosystems and to improve their management, especially using social-environmental approaches, such as the DAPSI(W)R(M) framework.

SRS data presents an opportunity to analyse important environmental factors through new satellite generation, such as the sentinel missions from the EU, which are presenting free accessible data through their different platforms and providing already processed data. High resolution data are presenting an unprecedented knowledge about the coastal and marine environment. Moreover, rather than using the inertial navigation system, SAR data as an SRS application could support UAV navigation (Nitti *et al.*, 2015).

UAV is revolutionizing data acquisition for specific targets related to activities, pressures, and state change assessment. Increasing the levels of battery autonomy, reaching higher altitudes, networking capability, and lowering costs are advancing research on the coastal environment. Coordination between a network of UAVs could help cover larger areas (Marques *et al.*, 2015).

SS sensors and their automation are increasing in efficiency and efficacy of data precision, through the technology's development. Sampling surveys for oceans are expensive and time-consuming. Therefore, USV and UUV are bringing insights and knowledge about deep-sea life, habitats, sediment, and water quality. The integration of datasets from different sensors has provided a growing ecological understanding of coastal and marine species for conservation purposes.

RS technologies are facilitating the policing of illegal activities, such as illegal fisheries, illegal sand mining, overfishing, vessel waste discharge, and oil spills that can negatively impact the ecosystem services provided by coastal and marine environments.

Application of algorithms to RS data are useful to develop an understanding of the environment. For instance, artificial neural network algorithms have been applied for statistical regression, image classification, image segmentation, and many other aspects of RS processing (Abu Qdais and Shatnawi, 2019). Furthermore, deep learning algorithms for RS imagery analysis are rising in popularity, which can perform image fusion and registration, object detection, land use and land cover classification, segmentation, object detection, and even accuracy assessment (Ma *et al.*, 2019), which will provide significant progress to the analysis of RS imagery of coasts and marine ecosystems (Gonzalez *et al.*, 2016).

Approaches to augmented reality will provide a new type of knowledge. RS data can be used to virtually reconstruct coastal and marine environments. Stakeholders and the larger public will be able to view, analyse, and interact with these environments (Bartolini *et al.*, 2018).

The Internet of Things (IoT) systems are playing a role in advancing the development of different coastal and marine environments by accessing, securing, managing, and controlling data infrastructures (G. Xu *et al.*, 2019; Granell *et al.*, 2020). This allows the monitoring of environmental conditions by communicating data from different networks into a single infrastructure. Data privacy protection, big data transmission, and data integration and processing on a large scale through IoT present a big opportunity to understand the environment.

Model-based RS data and free access to RS images through collaborative initiatives, such as the Copernicus Data and Information Access Services, at a regional level (EU), have facilitated information access to processed data. This has boosted users' innovation and created new research perspectives (Groom *et al.*, 2019; Le Traon *et al.*, 2019).

The incorporation of RS products into integrated coastal and marine management frameworks, such as DAPSI(W)R(M), is key to map information in a structured way. Such information can support the analysis of these complex ecosystems and presents a greater opportunity to achieve sustainable development.

VII. CONCLUSION

RS technologies have become an essential tool to support the coastal and marine integrated management framework, such as the DAPSI(W)R(M) application. The use of RS has expanded rapidly, and data available from different sensors has increased their utility. SRS, ARS, UAV, USV, UUV, and SS advances provided accurate measurement and mapping of numerous parameters associated with the DAPSI(W)R(M) components, from detecting to quantifying and monitoring activities, pressures, state changes, and impact (on welfare).

This chapter focuses on the relevant RS research related to coastal and marine ecosystems through an integrated coastal and marine environmental management framework and shows the role of emerging RS technologies to support this integration and to support the implementation of environmental directives policies, such as WFD, MSFD, SDG, and OHI.

RS presents many opportunities to improve our understanding of coastal and marine ecosystems. Nevertheless, there are still challenges and significant shortcomings related to RS application. These include technological advances, affordability and access, legal issues, fragmented knowledge, data communication, and dissemination.

Harmonizing regional, national, international, and interdisciplinary efforts between RS, coast and marine experts, as well as other stakeholders are essential. This can generate advanced knowledge to achieve sustainable development of our coasts and marine ecosystems. Future studies should focus on the contribution of RS technologies to the use and best practices for the management of the coastal zone.

CHAPTER 3: THE DAPSI(W)R(M) FRAMEWORK APPLIED TO THE NADOR LAGOON AND INTERCONNECTIONS WITH RS TECHNOLOGIES

The main objective of this chapter, is the application of the DAPSI(W)R(M) for the management of social-environmental and economic information's of the Nador lagoon, including collection, processing, analysing and providing recommendations. This, will help describing the preliminary results to identify the major issues and structuring them which will facilitate the decision-making process. In the following, each of the mentioned steps will be explained and detailed.

I. The DAPSI(W)R(M) problem-structuring framework applied to the Nador lagoons using RS.

I.1. Drivers

The drivers behind using the Nador lagoons are raising from the local population' needs at an individual scale for their survival. Each driver has a set of indicators (Fig.39). From the bottom line to the lines the drivers are totally fulfilled with respect to Nador lagoon, this shows the importance of such a socio-ecological and economical ecosystem.

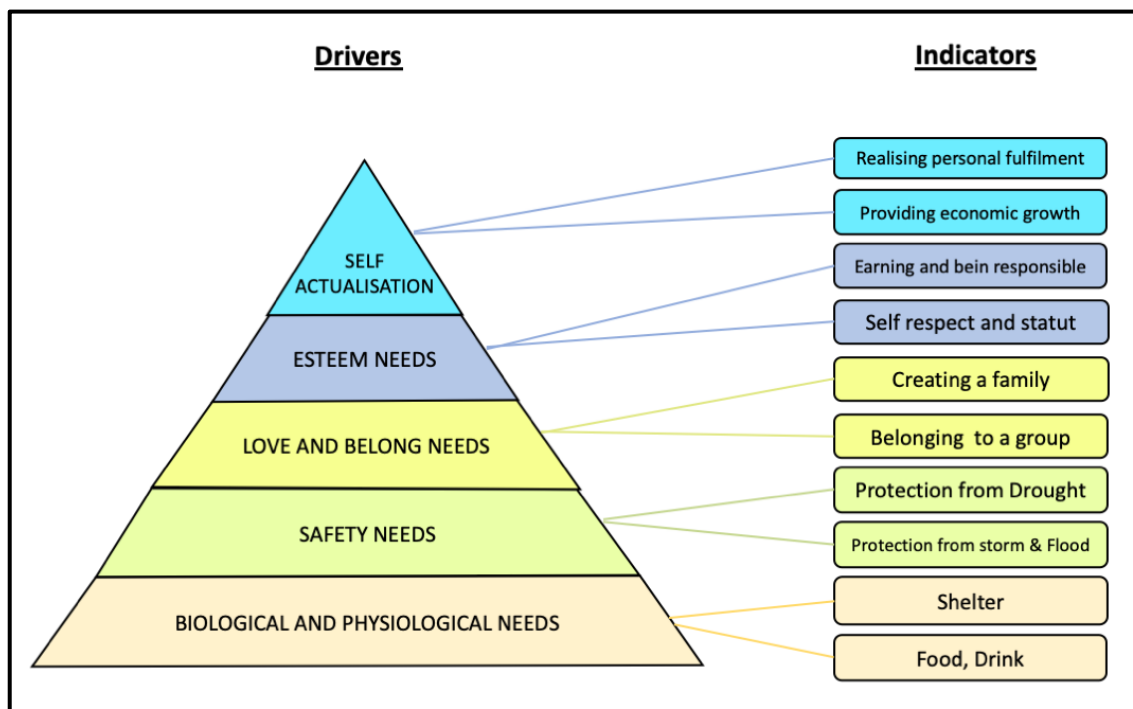


Figure 39: Drivers behind the use of the Nador lagoon (using Maslow pymarid)

I.2. Activities

Each driver requires one or different activities to achieve all needs. The main associated activities by sectors to each driver are shown in the (Fig.40) which represent the connection between both.

There are variety of activities that were found in the Nador lagoon (Fig.41). The major economic activities in the Nador lagoons are agriculture, extraction of living of living resources (mainly fishing), urbanization, tourism and recreation. These are followed by coastal infrastructures, damming of streams, navigational dredging, golf, transport, land-based industry shipping and livestock raising.

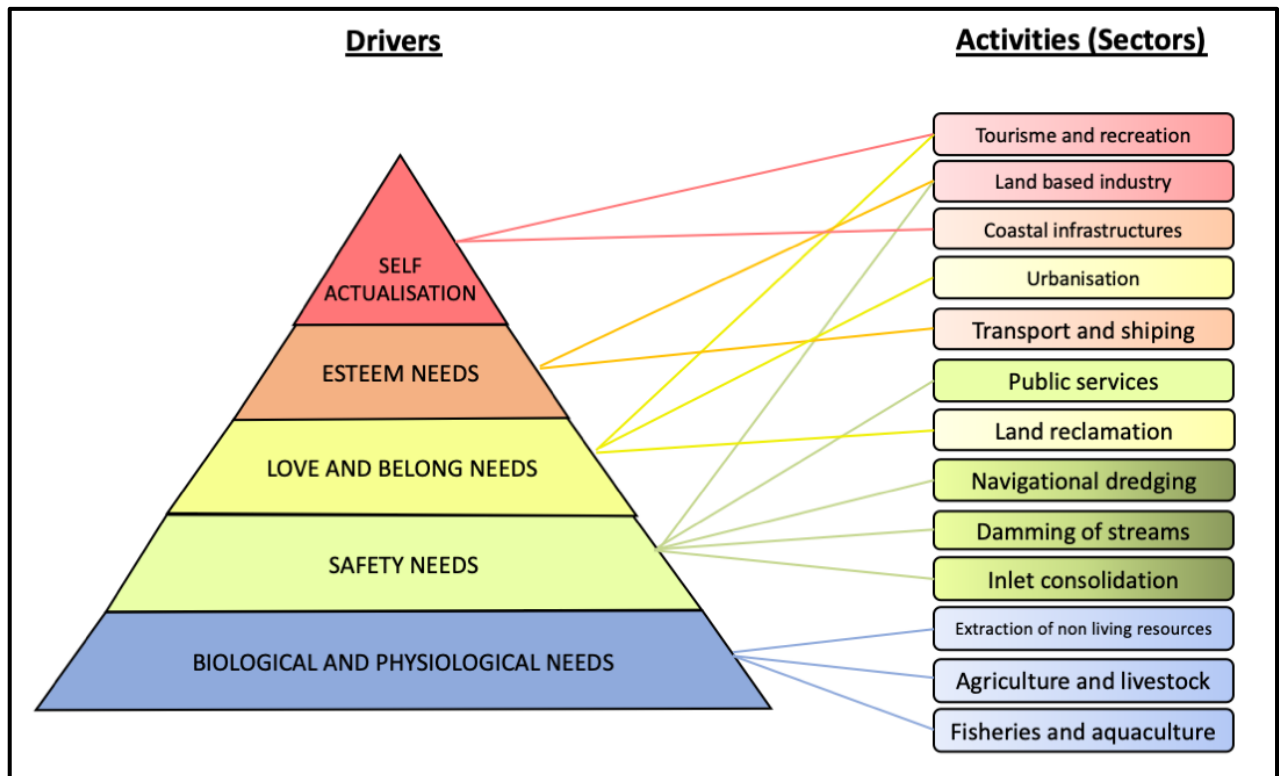


Figure 40: Interconnection between drivers and sectorial activities in the Nador city

As the Nador city is considered an urban, agricultural and industrial hotspot in the Northern region of Morocco. Thus, different Mega project were developed and currently developing such as the Marchica-Med tourism project that is dedicated to attract tourist and investors.

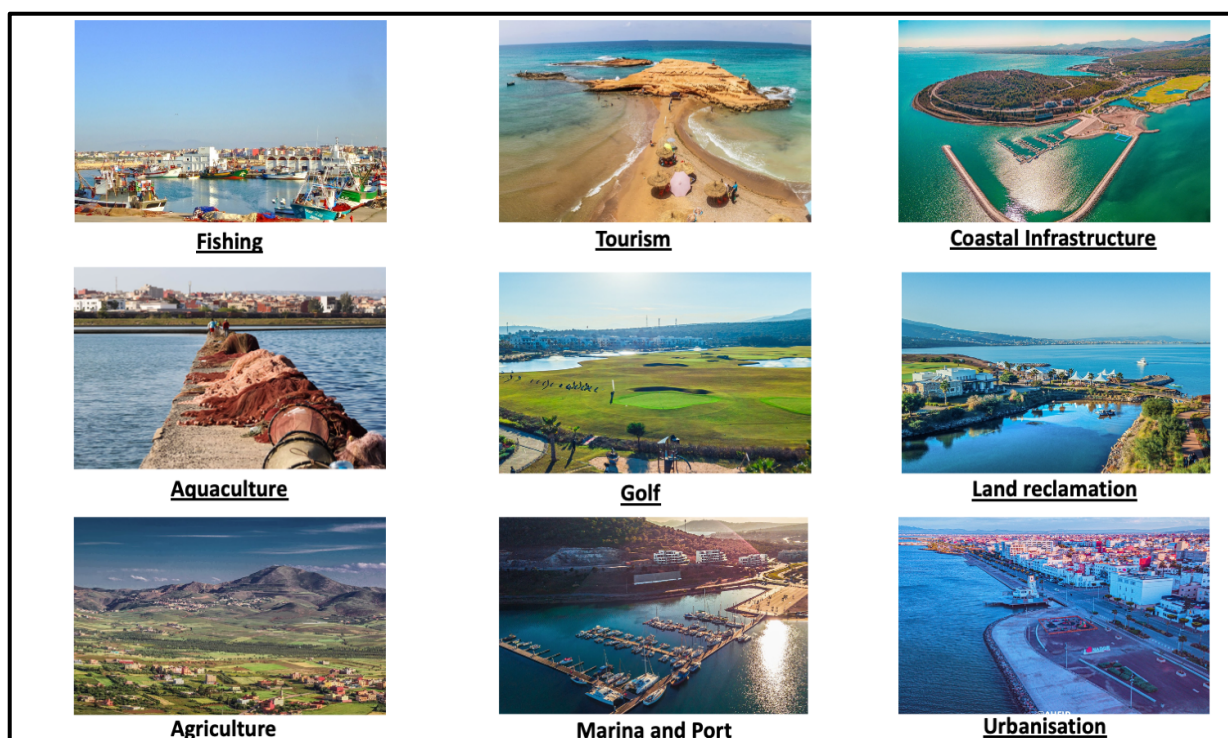


Figure 41: Major sectorial activities in the Nador lagoon

I.3. Pressures

Direct pressures to the environment and to the human welfare are triggered mainly by social and economic development labelled as activities.

The map below (Fig.42) list general two types of pressures on the lagoon. The Endogenic Managed Pressures such as phosphorus and nutrient enrichments and introduction of organic matter from agriculture, litter from urban growth, introduction of synthetic compound and non-synthetic compounds from industries, underwater noise from transport and fishing, change in siltation, introduction of non-indigenous species from aquaculture and many other substances. Then, the Exogenic Unmanaged pressures from natural variability and events, such as the sea-level rise, salinity change regime and inundation.

One of main pressures in this area is the nutrient loading which contributed for decades to the eutrophication of the Nador lagoon is the nutrient loading. This can be related to many pressures in form of effluents from domestic and industrial sewage containing synthetics and non-synthetics compounds, organic matter, as well as the form of nutrients and phosphorus inputs from agricultural runoff (e.g. fertilizers use) and feedlots which can change following the seasonal variability of a population, especially in high seasons. Furthermore, the rivers surrounding the lagoon drain more distant pollution.

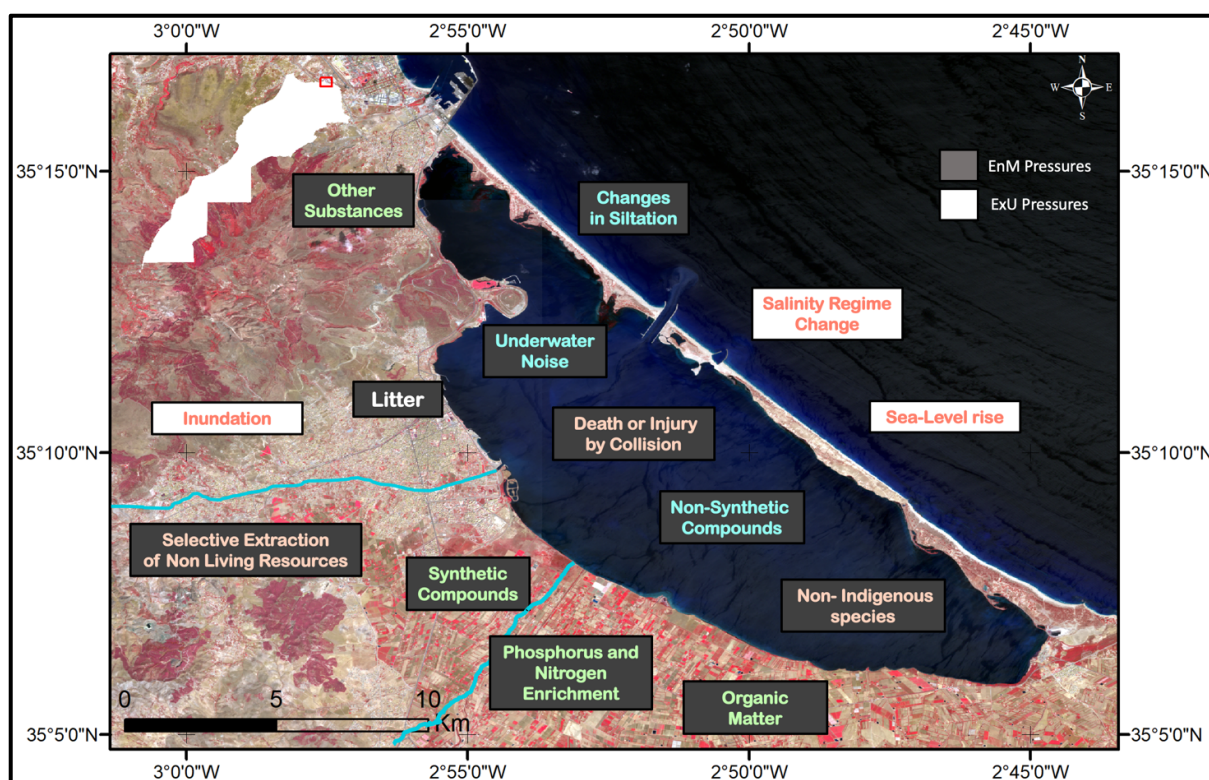


Figure 42: Existing pressures related to Nador lagoon. EnMP : Endogenic Managed Pressures ; ExUP: Exogenic Unmanaged Pressures

The integration of one or multiple data extracted from one or different sensors and models represents a cost-effective way of information about one or different activities, pressures, state changes, allowing to detect the current and possible threats to the environments such as the case of Nador lagoon. The results of using RS application related to Phosphorus and nitrogen enrichments will be shown in the next section (see I.4 - state changes).

I.4. State changes

The environmental state of the Nador lagoon ecosystem has been changing over time, as a result of the mentioned components above.

According to the Action Plan for the Mediterranean, the Nador lagoon was classified as a 'hotspot of the Mediterranean pollution which related to the different activities and as a consequence of different pressures. The existing activities and pressures that are coming for the terrestrial and the marine parts of the lagoon affect the state of the lagoon environment (Maanan *et al.*, 2015b). The main source of pollution leading to a stat change are urban growth, agricultural derivatives and the different industrial effluents surrounding the lagoon.

The identified state changes (Fig.43) were linked to one or different pressures, such as the pH changes, turbidity plumes, degradation of water quality, changes in the *physical parameters* ,

changes in the *ecological parameters* such as habitat (fauna and flora), harmful algal blooms and changes in the *geo morphodynamic characteristics* (subsidence, landslides, ...).

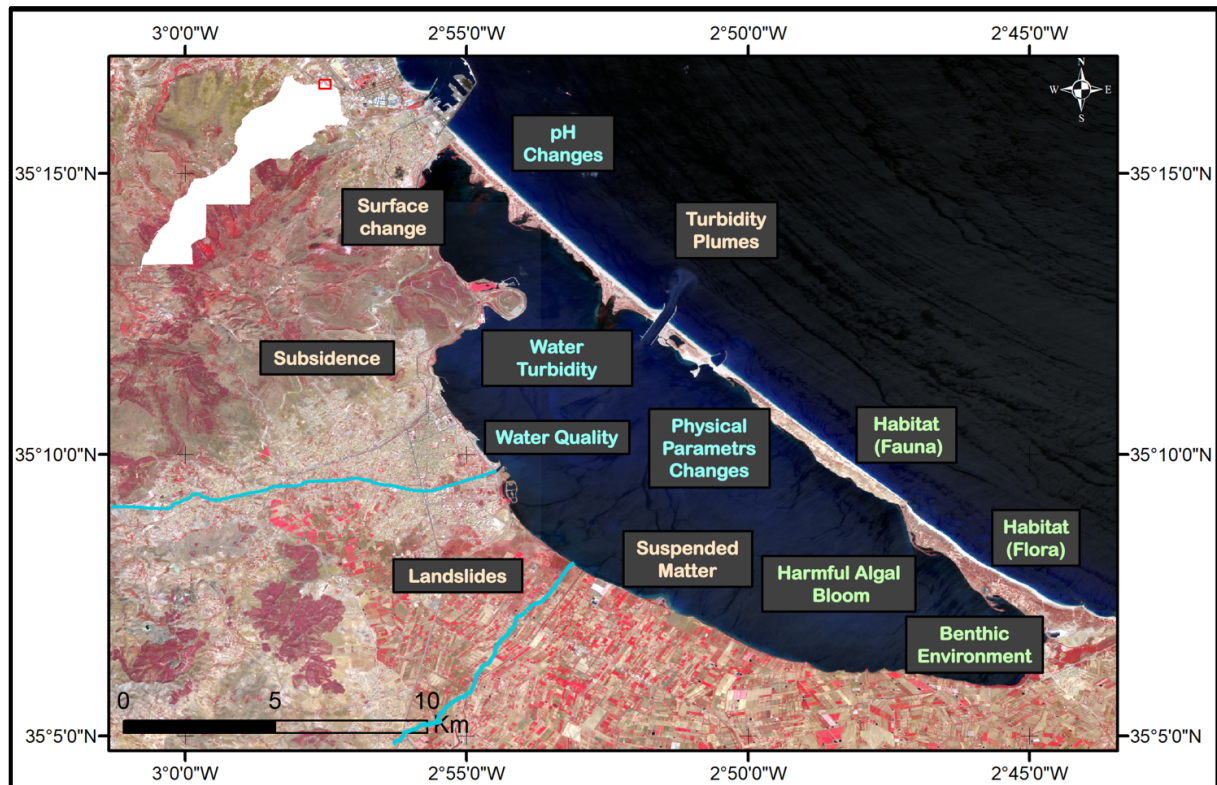


Figure 43: State changes related to Nador lagoon

The Chlorophyll concentration is an indicator of the algae amount in the ecosystem and therefore represents the input of energy and biomass into the aquatic system vis the photosynthesis process. This algae development is often related to the input of nutrient and the high concentrations of the chlorophyll is usually a results of pollution from communal sewage and/or agricultural runoff.

For this purpose, SRS images were used from the Sentinal hub platform to assess the ‘water quality’ index (Zlinszky and Padányi-Gulyás, 2020), which represent a combination of chlorophyll concentration and suspended sediment concentration.

The images were selected in 3 different times between 2018 and 2020 from Sentinel 2 satellite (Fig.44) .

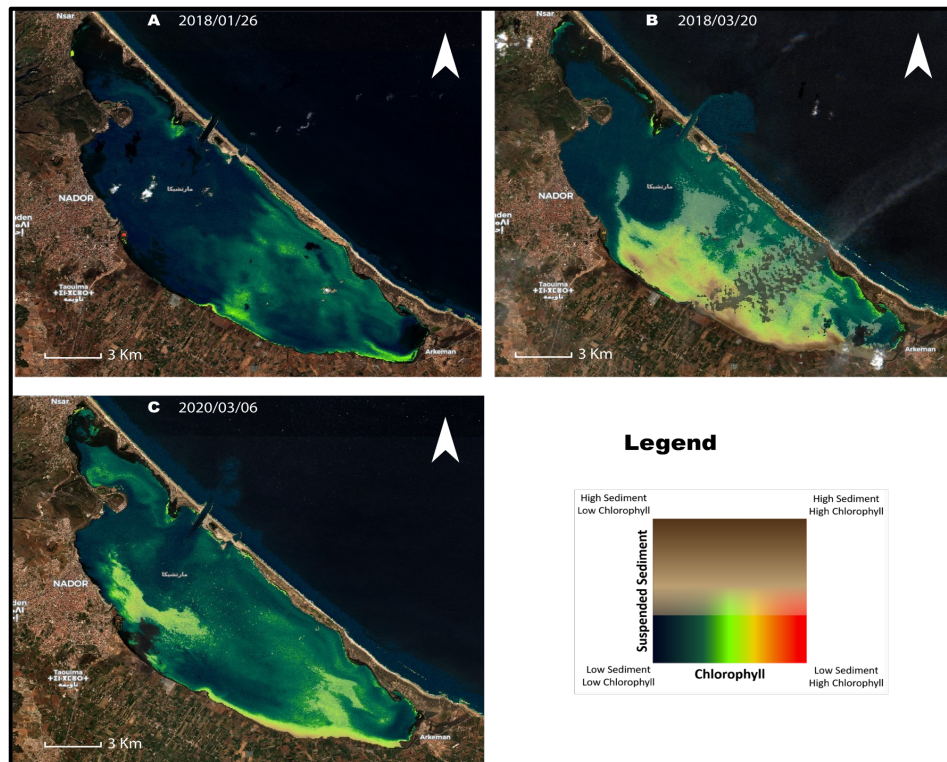


Figure 44: Water quality index extracted from Sentinel 2 images in different times.

The results show the presence of the chlorophyll and sedimentation in the Nador lagoon. The Eastern part of the lagoon has most of the times a higher chlorophyll and low sedimentation. Figure 44.b, shows a high sedimentation and high chlorophyll near the coastal part of the agricultural areas which are the nutrient loading in the ecosystem.

The pressures that led to known eutrophication phenomena in the lagoon Nador does not affected the biodiversity and living resources but causes significant damage to human welfare.

Due to the degradation of the algae from the different pressures, the lagoon has known an increase of the oxygen consumption causing a state change of the ecosystem and leading to eutrophication.

1.5. Impact (on Welfare)

The variety of drivers, activities, pressures and state changes of the environments, which acted synergically, has led to different impact on the human welfare regarding the Nador.

The degradation of the natural resources would affect the stakeholders using the lagoon as their main environments for earning economic benefits. Therefore, different forms of impact could be identified regarding the final ecosystem services from provisioning to supporting to cultural services.

The main social-economic impact are the loss of incomes and jobs leading to unemployment, loss of touristic income, increase in the fish prices, loss of healthy climate and the aesthetic benefits.

I.6. Responses (as Measures)

The conceptual overview of the main drivers, activities, pressures, state changes and impact on human welfare, gives an insight knowledge to establish responses and measures as baseline scenarios for the integrated environmental management of the Nador lagoon. The ultimate objective of the responses should aim to make inferences for the management-related threats that could be implemented in order to improve the ecosystems quality that will bring more ecosystem services.

An example of management options (as measures) in forms of policies are listed in the Table 18 below.

Due to the lack of available and sufficient related data to asses each component of the DAPSI(W)R(M), The indicators selection process has been concentrated on the available but key indicators. However, the RS technologies could fill this gap.

Table 18: Policies Management options

No .	Management Options (as Measures)
<u>1</u>	Do nothing
<u>2</u>	Updating and extend the Waste Water Treatment Plants surrounding the lagoon (To cover Urbanization and tourism) to limit effluents .
<u>3</u>	Implementing collective sanitation systems and networks for the rural order to meet discharges standards .
<u>4</u>	Arresting urban development close to shores to limit massive urbanisation .
<u>5</u>	Monitoring the rivers discharges
<u>6</u>	Developing an Agricultural Waste Management System (AWMS) to limit nutrient, phosphorus and organic matter effluent .
<u>7</u>	Using economic instruments (e . g . polluters pay principle) to encourage economic actors to treat their waste and initiate nutrient trade
<u>8</u>	Developing eco-friendly touristic activities in a sustainable perspective .
<u>9</u>	Preserving the most sensitive natural habitat
<u>10</u>	Increasing water circulation by dredging
<u>11</u>	Organising annual stakeholders meeting to limit conflicts among them .
<u>12</u>	Protecting the natural environmental from natural risks such as sea-level rise and flooding events
<u>13</u>	Campaign awareness for farmers in order to switch to bio-agriculture products

II. Conclusion

The application of an integrated environmental management framework (DAPSI(W)R(M)) to assess and analyse the Nador lagoons (Fig.45), helped to identify the causes of environmental threats, to examine their effects to social and economic aspect and to suggest management options that improve the environmental health and provide a sustainable development. Indeed, the RS technologies could help to fill the gap in missed data to better understand these socio-ecological systems. However, their applications are not meant to be exhaustive, but rather to provide knowledge on their use for holistic management, such as supplying missing data.

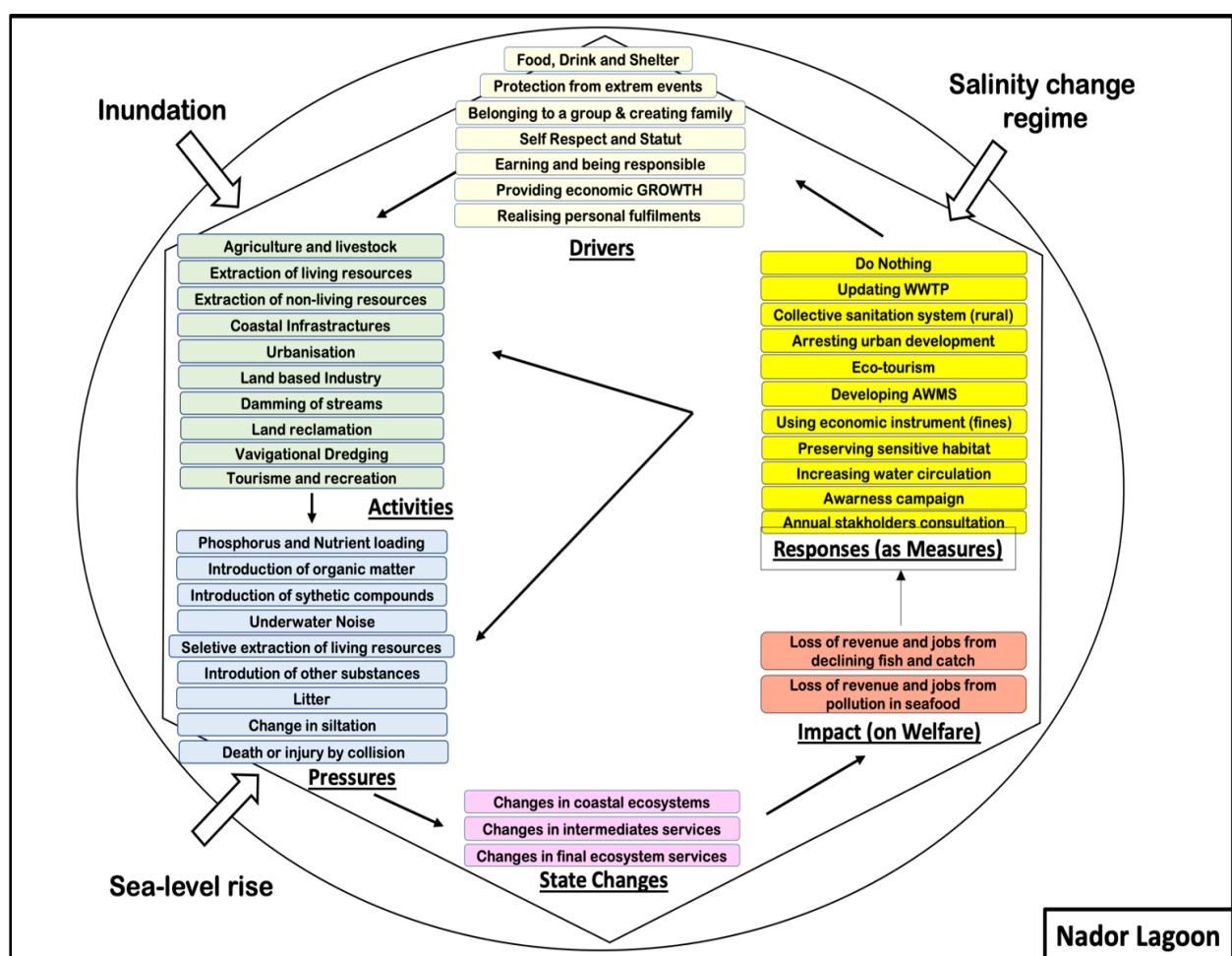


Figure 45: Graphical abstract of DAPSI(W)R(M) application to Nador lagoon

GENERAL CONCLUSION, RECOMMENDATIONS AND PESPECTIVES

Coastal and marine areas, including lagoons are ecosystems with an important ecological role as habitats, but they also provide many essential socio-economic goods and services for the inhabitants in the surrounding communities. However, the unsustainable use of these ecosystems has led to different issues worldwide.

Two main conclusions are drawn from this thesis. The first one is to provide an integrated assessment and management to coastal lagoons of North African and the second one to fill the gap founded in these lagoons and that can be found in all coastal and marine areas worldwide while using the RS technologies.

As the North African coastal lagoons are complex environments, thus a multi-disciplinary approach was needed for their analysis and their management.

The application of the DAPSI(W)R(M) framework in the context of this research helped to identify differences and similarities among the 11 North African coastal lagoons chosen as study sites (Khenifiss, Oualidia, Nador, El Mellah, Bizerte, Tunis, Boughrara, Frawa, Marsa Matrouh, Bardawil, Burullus). Many drivers, activities, and pressures that affected and still affecting the ecological state of these ecosystems and had an impact on human welfare have been identified. The behavior of users founded to be similar across North African lagoons but the Khenifiss lagoon remains an exception as a pristine ecosystem. Moreover, the use of such an approach for lagoons management is a new application in the North African countries. A list of responses as measures has been suggested, which could help to achieve sustainable development and could deliver more ecosystem services.

The approach used in this research was different from the previous uses (Newton et al., 2014; Dolbeth et al., 2016)

However, the application of such an integrated approach faced a data knowledge gap to assess the different activities, pressures, state changes and the impact (on welfare) of the coastal and marine environments as shown in the North African lagoons context and which actually could be founded in different coastal and marine areas around the world. Thus, the RS technologies could help to fill this gap as they have become an essential tool to support the coastal and marine integrated management framework, such as the DAPSI(W)R(M) application.

Therefore, this research provided an overview of RS uses for an expanded DPSIR framework. It has been concluded that the use of RS technologies such as SRS, ARS, UAV, USV, UUV, and SS and their recent advances provided accurate measurement and mapping of numerous parameters associated with the DAPSI(W)R(M) components, from detecting to quantifying

and monitoring activities, pressures, state changes, and impact (on welfare), such as the case of the Nador lagoon.

The Earth observation techniques can be applied for the implementation of international environmental directives, such as WFD and MSFD, and for the assessment of global indices such as the OHI. Furthermore they, can help improve environmental understanding for better resource management and attaining SDGs. Moreover, the challenges, knowledge gaps, and opportunities of RS for DAPSI(W)R(M) were highlighted.

The results of this PhD thesis show that the DAPSI(W)R(M) approach is a valuable and important tool for providing information to improve coastal and marine environmental assessment and management.

The achievements will give important contributions to North African scientific community as well for the marine and coastal managers and scientists worldwide to implement a holistic coastal and marine environmental management framework.

As perspectives of this research:

- The integrated approach used in the context of this thesis should be adapted for local specifics with detailed data and informations (ex. An individual lagoon).
- The implementation of measures should be followed by environment assessment studies of effectiveness and need to address timely responses solution.
- An increase of participation from citizens and raising their awareness regarding coastal and marine issue in order to ensure sustainability of management plans.
- The mapping of stakeholders for each ecosystem and developing a participatory approach for them to support greater collaboration, cross-sector working, interdisciplinarity dialogue.
- Further studies are needed to put into context the climate change issues as long-term challenges to coastal and marine areas as they will be the ongoing global issues.
- There is a need to generate data at agreeable standards which will support the assessment of individual parameters, will allow the scientific modelling and will evaluate socio-economical benefiteres to measure impacts.

I conclude by asserting the need of such research using a holistic integrated framework as a robust approach for sustainable coastal and marine areas.

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ANNEXES

- *Annexe 1: Articles published under this PhD Thesis*

Article 1: Social-Environmental Analysis for the Management of Coastal Lagoons in North Africa.

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Social-Environmental Analysis for the Management of Coastal Lagoons in North Africa

Badr El Mahrad^{1,2,3*}, Samuel Abalansa³, Alice Newton^{3,4}, John D. Icely³, Maria Snoussi⁵ and Ilias Kacimi²

¹ Murray Foundation, Brabners LLP, Liverpool, United Kingdom, ² Laboratory of Geoscience, Water and Environment (LG2E-CERNE2D), Department of Earth Sciences, Faculty of Sciences, Mohammed V University of Rabat, Rabat, Morocco, ³ CIMA, FCT-Gambelas Campus, University of Algarve, Faro, Portugal, ⁴ NILU-IMPACT, Kjeller, Norway, ⁵ Department of Earth Sciences, Faculty of Sciences, Mohammed V University of Rabat, Rabat, Morocco

This study provides an overview of 11 lagoons in North Africa, from the Atlantic to the Eastern Mediterranean. Lagoons are complex, transitional, coastal zones providing valuable ecosystem services that contribute to the welfare of the human population. The main economic sectors in the lagoons included fishing, shellfish harvesting, and salt and sand extraction, as well as maritime transport. Economic sectors in the areas around the lagoons and in the watershed included agriculture, tourism, recreation, industrial, and urban development. Changes were also identified in land use from reclamation, changes in hydrology, changes in sedimentology from damming, inlet modifications, and coastal engineering. The human activities in and around the lagoons exert multiple pressures on these ecosystems and result in changes in the environment, affecting salinity, dissolved oxygen, and erosion; changes in the ecology, such as loss of biodiversity; and changes in the delivery of valuable ecosystem services. Loss of ecosystem services such as coastal protection and seafood affect human populations that live around the lagoons and depend on them for their livelihood. Adaptive management frameworks for social-ecological systems provide options that support decision makers with science-based knowledge to deliver sustainable development for ecosystems. The framework used to support the decision makers for environmental management of these 11 lagoons is Drivers-Activities-Pressures-State Change-Impact (on Welfare)-Responses (as Measures).

Keywords: coastal lagoons, North Africa, water management, environmental assessment, adaptive management frameworks, social-ecological systems, DAPSI(W)R(M) a modified DPSIR, ecosystem services

HIGHLIGHTS

- A social-environmental analysis of 11 North African coastal lagoons.
- The behavior of users is similar across North African lagoons.
- Responses (as measures) to problems are identified.
- Adaptive management of coastal lagoons can deliver more ecosystem services.

INTRODUCTION

Coastal lagoons are important zones for life between the land and the sea. They are one of the most productive environments and deliver ecosystem services (ES) that provide many ecological,

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***Correspondence:**
Badr El Mahrad
badr.elmahrad@gmail.com

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Article 2: Environmental Conditions, Vulnerability and Future Perspective of Coastal Water Bodies in Morocco

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RESEARCH-ARTICLE

Environmental Conditions, Vulnerability and Future Perspective of Coastal Water Bodies in Morocco

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Authors: [Badr El Mahradi](#), [Ilias Kacimi](#), [Narjiss Satour](#), [Alice Newton](#), [John David Icely](#),
[Maria Snoussi](#), [Samuel Abalansa](#) [Authors Info & Affiliations](#)

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Article 3: Contribution of Remote Sensing Technologies to a Holistic Coastal and Marine Environmental Management Framework: A Review.



Article

Contribution of Remote Sensing Technologies to a Holistic Coastal and Marine Environmental Management Framework: A Review

Badr El Mahrad ^{1,2,3,*}, Alice Newton ³, John D. Icely ^{3,4}, Ilias Kacimi ², Samuel Abalansa ³ and Maria Snoussi ⁵

¹ Murray Foundation, Brabners LLP, Horton House, Exchange Street, Liverpool L2 3YL, UK

² Laboratory of Geoscience, Water and Environment, (LG2E-CERNE2D), Department of Earth Sciences, Faculty of Sciences, Mohammed V University of Rabat, Rabat 10000, Morocco; iliaskacimi@yahoo.fr.

³ CIMA, FCT-Gambelas Campus, University of Algarve, 8005-139 Faro, Portugal; anewton@ualg.pt (A.N.); john.icely@gmail.com (J.D.I.); abalansas@gmail.com (S.A.)

⁴ Sagremarisco, Apartado 21, 8650-999 Vila do Bispo, Portugal

⁵ Department of Earth Sciences, Faculty of Sciences, Mohammed V University of Rabat, Rabat 10000, Morocco; snoussi@fsr.ac.ma

* Correspondence: badr.elmahrad@gmail.com

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Abstract: Coastal and marine management require the evaluation of multiple environmental threats and issues. However, there are gaps in the necessary data and poor access or dissemination of existing data in many countries around the world. This research identifies how remote sensing can contribute to filling these gaps so that environmental agencies, such as the United Nations Environmental Programme, European Environmental Agency, and International Union for Conservation of Nature, can better implement environmental directives in a cost-effective manner. Remote sensing (RS) techniques generally allow for uniform data collection, with common acquisition and reporting methods, across large areas. Furthermore, these datasets are sometimes open-source, mainly when governments finance satellite missions. Some of these data can be used in holistic, coastal and marine environmental management frameworks, such as the DAPSI(W)R(M) framework (Drivers–Activities–Pressures–State changes–Impacts (on Welfare)–Responses (as Measures)), an updated version of Drivers–Pressures–State–Impact–Responses. The framework is a useful and holistic problem-structuring framework that can be used to assess the causes, consequences, and responses to change in the marine environment. Six broad classifications of remote data collection technologies are reviewed for their potential contribution to integrated marine management, including Satellite-based Remote Sensing, Aerial Remote Sensing, Unmanned Aerial Vehicles, Unmanned Surface Vehicles, Unmanned Underwater Vehicles, and Static Sensors. A significant outcome of this study is practical inputs into each component of the DAPSI(W)R(M) framework. The RS applications are not expected to be all-inclusive; rather, they provide insight into the current use of the framework as a foundation for developing further holistic resource technologies for management strategies in the future. A significant outcome of this research will deliver practical insights for integrated coastal and marine management and demonstrate the usefulness of RS to support the implementation of environmental goals, descriptors, targets, and policies, such as the Water Framework Directive, Marine Strategy Framework Directive, Ocean Health Index, and United Nations Sustainable Development Goals. Additionally, the opportunities and challenges of these technologies are discussed.

Keywords: remote sensing; DPSIR; coastal and marine management; environmental policies and directives; WFD; MSFD; ocean health index; sustainable development goals

- *Annexe 2: Articles published as an outcome of international Collaboration*

Article 1: Groundwater Vulnerability Assessment Using Drastic and GIS in Deveh Aquifer, Syria

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RESEARCH-ARTICLE

Groundwater Vulnerability Assessment Using Drastic and Gis in Deveh Aquifer, Syria

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Authors:  [Rasha Hassan](#),  [Badr El Mahrad](#),  [Samia Chiban](#) [Authors Info & Affiliations](#)

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Article 2: Time series of flood mapping in the Mekong Delta using high resolution satellite images

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Time series of flood mapping in the Mekong Delta using high resolution satellite images

D A Dinh^{1,2}, B Elmahrad^{1,3}, P Leinenkugel² and A Newton¹

¹ CIMA, FCT-Gambelas Campus, University of Algarve, 8005-139 Faro, Portugal

² German Remote Sensing Data Center (DFD), Earth Observation Center (EOC), Aerospace Center (DLR), Oberpfaffenhofen, Wessling, Germany

³ Department of Earth Sciences, CERN2D, Faculty of Sciences, Mohamed V University, Rabat, Morocco

E-mail: dinhdieuanh1319@gmail.com

Abstract. The Mekong Delta, located in Southern Vietnam, is one of the most affected areas in the world by climate change and sea level rises, especially flooding. Therefore, flood mapping is essential for understanding the flood regime and mitigating its impacts. Remote sensing and GIS can support the accurate and area wide evaluation of floods. In this study, high spatial resolution synthetic aperture radar (SAR) and optical data were used to generate a dense satellite data time series for analysing the spatio-temporal patterns of flooding in the Mekong Delta. To derive water masks, a total of 777 Sentinel-1, 515 Sentinel-2 and 57 Landsat-8 scenes were used to generate cloud free water masks at a 10m spatial resolution in regular 10-day intervals throughout the observation period of hydrological years 2016-2017. The results show a spatial explicit information on the core zones of the seasonal flooding processes for the entire Mekong Delta and their effect of using floodwater for rice cultivation. The outcome maps provide an overall understanding of Mekong Delta flood patterns and many valuable information for policymakers and water resources managers.

1. Introduction

A flood occurs when excess water upstream flows over river banks or dikes to the floodplain, especially, when the water flow submerges area that is generally dry. Inundation is affected by floods. Flood water may be freshwater from upstream or/and saltwater from the sea due to the tide [1]. Flooding has severe economic and social impacts [2]–[4]. However, it has also environmental and socio-economic benefits [5] such as the annual flooding which is also called “beautiful” flood supplied freshwater for irrigation and domestic use [6], increased fishery resources [7], improved navigation transport, brought about more natural fertilizer, flushed contaminated water caused by sulfate soils and transported salted water towards the sea such as the case of South China Sea [8].

Flooding is increasing in frequency and magnitude along with sea level rise, seasonal tropical storms and high tides in the Mekong Delta [1]. The Mekong Delta has been identified as one of the most sensitive and exposed regions to climate change and sea level rise phenomena [8]. In the official climate change and sea level rise report by the Ministry of Natural Resources and Environment, it is estimated that 21%, 28.2% and 38.9% of the Mekong Delta area will be flooded if the sea level increases by 80cm, 90cm and 100cm respectively [9]. Floods often impact large regions, which are difficult to access from



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