



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

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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,

cultural, and socioeconomic benefits, supporting a range of natural services that are highly valued by society (Gönenç and Wolflin, 2005; Newton et al., 2018). In the specific case of North Africa, coastal lagoons have a 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. 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 (see section “Discussion”).

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 (SESs) continue to be heavily impacted by human activities, such as extraction of freshwater and urbanization, as well as the development of economic sectors, for example, fisheries, agriculture and tourism. 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., 2009a; 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 section **Supplementary Material**).

The variety of issues in North African coastal lagoons (ecological functioning, biodiversity, productivity, human uses) requires conceptual models to organize, understand, and clarify issues and recapitulate information in a standard, logical, and hierarchical method (Patrício et al., 2016). The DAPSI(W)R(M) [Drivers-Activities-Pressures-State Changes-Impacts (on Welfare)–Responses (as Measures)] framework (Elliott et al., 2017) is the conceptual model that has been followed for the social environmental analysis of coastal lagoons in North Africa. In the context of this study, *State* refers to environmental state (e.g., water quality), ecological state (e.g., biodiversity), and consequently state of ES. This analysis enables local planners and state regulators to identify management solutions and measures for adaptation to changes in the lagoon ecosystems. An important aspect of these measures is the maintenance and improvement in the ES that these lagoons provide for human welfare.

MATERIALS AND METHODS

Study Sites: Distribution of North African Lagoons

North Africa is defined as the Southern Mediterranean Region 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 (**Figure 1**).

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.

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; and 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 (names in white on black background, **Figure 1**).

Data Sources and Collection

The data 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 to 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 “gray” 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 Kenifiss).

The search words were applied in English, French, and Arabic. Most of the articles listed in the *References* 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, which was consulted for this review, but this is not listed in the *References*.

The search keywords that were used, both singly and in combination, were as follows: “name” of the lagoon, including local variations on their names, see section “Confusion About Nomenclature of Lagoons in the Context of North African Lagoons”; “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, and then the full texts were screened. Many studies were removed because of 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, and underwater noise). The reported presence and 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).

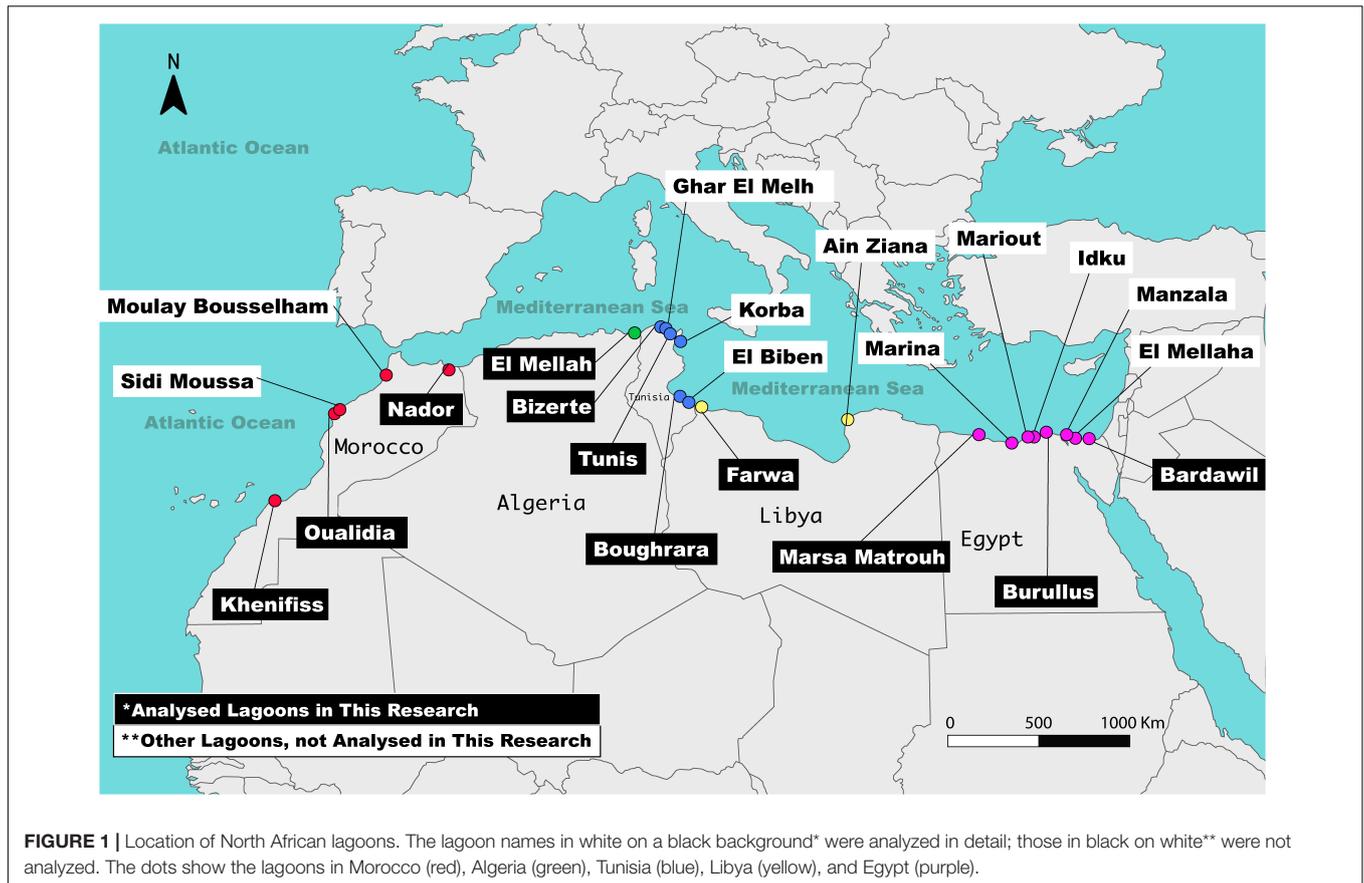


FIGURE 1 | Location of North African lagoons. The lagoon names in white on a black background* were analyzed in detail; those in black on white** were not analyzed. The dots show the lagoons in Morocco (red), Algeria (green), Tunisia (blue), Libya (yellow), and Egypt (purple).

Analytical Framework

DAPSI(W)R(M), a social–ecological framework for adaptive management from Elliott et al. (2017), was used for the analysis of the lagoons. This framework has evolved from earlier versions (Gari et al., 2015) starting with the PSR (Pressures–State–Response) framework proposed by Rapport and Friend (1979) and then developed and supported by the Organization for Economic Cooperation and Development (OECD) to organize its work on environmental policies and reporting (OECD, 1994). A later version is the DPSIR [Drivers–Pressures–State–Impacts (on Welfare)–Responses (as Measures)] used by, among others, the US Environmental Protection Agency (EPA, 1994), the United Nations Environment Programme (UNEP, 1994), the European Environment Agency (EEA, 1995), and the European Commission (EU, 2000). Patrício et al. (2016) and Elliott et al. (2017) highlight the anomalies and focus on the confusions of each component of DPSIR as a reason for improving the framework; for practicable management purposes, they advocate an extension of the framework to DAPSI(W)R(M). In this version, Drivers or driving forces indicate the basic needs of humans (Maslow, 1943), such as food, transport, and goods. These needs are addressed by society through socioeconomic **Activities**, such as fishing, aquaculture, and building infrastructure that have effects that produce **Pressures**, such as overextraction of resources, input of nutrients and/or heavy metals, pH changes, and so on. These effects lead to **State**

changes on the ecology of the environment, as well as on the intermediate and final ES (Elliott et al., 2017). These changes have **Activities** (on human **Welfare**), such as provisioning services (e.g., fish food), regulating services (e.g., healthy climate), and cultural services (e.g., tourism). **Responses** (as **Measures**) to changes resulting from drivers, activities, and pressures require scientific knowledge to produce appropriate laws for governance, as well as a range of economic mechanisms and technologies to implement the appropriate management (Wolanski and Elliott, 2015; Elliott et al., 2017).

RESULTS

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, and so on.

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 among 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, and 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 fulfillment. 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 an excellent case study not only for North Africa but also for the other countries in Africa and elsewhere.

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 1** summarizes some of the more important activities (adapted from Smith et al., 2016) occurring in these lagoons that are presented in more detail in the following sections.

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 are available for the different lagoons.

Extraction of Living Resources and Aquaculture

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 1,157 tons in 2012, which represents an increase of 241%. The monthly net profit per boat is approximately 222 Euros (2,465 Moroccan Dirhams). Overall, the main fish catches are eel (i.e., *Anguilla anguilla*), bream (i.e., *Sparus aurata*), and gray and red mullet (i.e., *Mullus barbatus*). Other catches include cuttlefish, octopus (i.e., *Octopus vulgaris*), and shrimp (i.e., *Penaeus 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, whereas 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 approximately 40 tons. The production comprises eels (58%), followed by mullet (31%) represented by *Mugil cephalus*, *Liza aurata*, *Liza saliens*, *Liza ramada*, and *Chelon labrosus*. There is also harvesting of mollusks 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 the Enterprise Nationale Algérienne de Pêche-Unité Aquacole; they are all male with an average age of 44 years, supporting a total of 67 children (Food and Agriculture Organization, 1982).

The catch from Farwa lagoon (Libya) is 26 tons annually, mainly fish, shellfish, and octopus, but there are 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 depends on the size of the lagoon (both area and depth), as well as the population surrounding the lagoon.

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 more than 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 approximately 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 et al., 2016; Nassar et al., 2018).

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

TABLE 1 | The major economic sectors and activities in North African lagoons: “X” represents documented, and “?” undocumented* activities.

| Country | Morocco | | | Algeria | | Tunisia | | Libya | Egypt | | | |
|--|---------|-----------|----------|---------|-----------|---------|-------|-----------|-------|---------------|----------|----------|
| | Lagoon | Khenifiss | Oualidia | Nador | El Mellah | Bizerte | Tunis | Boughrara | Farwa | Marsa Matrouh | Burullus | Bardawil |
| Activity/economic sector | | | | | | | | | | | | |
| Extraction of living resources | X | X | X | X | X | X | X | X | X | X | X | X |
| Aquaculture | X | X | X | X | X | X | X | X | X | X | X | |
| Agriculture | | X | X | X | X | | | | ? | X | X | X |
| Golf | | | X | | | | | | | X | | |
| Tourism and recreation | | X | 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 | X |
| Land reclamation | | | | | | | X | | | X | X | X |
| Damming of streams | | X | X | | | X | | | | | X | |
| Inlet consolidation (hard structures that fix the position of the inlet) | | | X | | | X | | X | | X | | |
| Navigational dredging | | X | X | | | ? | X | X | | | X | X |
| Coastal infrastructure | | X | X | X | | | X | | | X | X | X |
| Transport and shipping | X | X | X | X | X | X | X | | X | X | X | X |

List of activities adapted from Smith et al. (2016). *Activity is mentioned in informal communications such as newspapers, websites, and so on.

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., 2015a), with barley occupying 56% of total area, olive trees nearly 22%, and other crops approximately 22%. Fishing activities, agriculture, and livestock production employ up to 46% of the working population in the region (Najih et al., 2015). 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, 34, 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 approximately 403 km² of the agricultural land in the Nile Delta (El-Amier et al., 2017; Orabi et al., 2017).

Tourism and 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. The seaside resort has a diversity of landscapes, and in summer, the population increases by 54,000¹ 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 seven 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, 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 7,000 workers (Mulazzani et al., 2017).

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.

¹www.hcp.ma

Nador lagoon in Morocco has several industrial activities, including mining and metallurgy, such as iron, pyrite, pyrrhotite, and 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 approximately 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, textiles, 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 three units with an annual production of 104,000 tons of ethylene dichloride, 60,000 tons of polyvinyl chloride, 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).

Urbanization, 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 2014². Recently, the Moroccan government through the “Marchica agency” has invested 4 billion Euros in seven new projects: Cité Atalayoun, Cité des 2mers, Nador new city, fisherman’s village, Baie des Flamants, Marchica Sport, and Les Vergers de Marchica, which are destined as houses, apartments, a harbor, and a research center and natural park for resident and touristic growth; some are constructed already, and some are still under construction.

The inlet located at the center 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 1,450-m east breakwater and the 1,350-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 (Figure 1). 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)³. 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 four harbors (Harbor of Bizerte, Menzel Abderrahmane harbor, Menzel Bourguiba, and The Carrier bay harbor parked) (Abidli et al., 2016).

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.

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, and 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, and gas and oil tankers, as well as military vessels. The Menzel Bourguiba harbor receives approximately 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 harbor has approximately 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 2,902 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 approximately 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, whereas larger boats contribute 80% within an annual production of approximately 272 tons (Mulazzani et al., 2017). In the Bardawil lagoon, 1,235 “feluccas” of 4 to 6 m are used for fishing activity. The Burullus lagoon has 2,098 boats where 2,049 are small “feluccas”

²www.hcp.ma

³http://dataportal.ins.tn/fr/Map

TABLE 2 | The existing pressures on North African lagoons: “X” represents documented and “?” represents undocumented pressures.

| Country | Morocco | | | Algeria | | Tunisia | | Libya | | Egypt | |
|---|-----------|----------|-------|-----------|---------|---------|-----------|-------|---------------|----------|----------|
| | Khenifiss | Oualidia | Nador | El Mellah | Bizerte | Tunis | Boughrara | Farwa | Marsa Matrouh | Burullus | Bardawil |
| Pressure | | | | | | | | | | | |
| 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 |
| Presence of underwater noise | X | X | X | X | X | X | X | X | X | X | X |
| Presence of 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 | | | | | |
| Water flow rate changes | | X | | | ? | X | X | | X | | X |
| pH changes | | X | | | | X | X | | X | X | X |
| Change in wave exposure | | | | | | | | | X | | |

List of pressures adapted from Smith et al. (2016).

(4–6 m), 41 are medium boats (6–8 m), and eight are large boats (> 8 m).

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 1, 2). The distribution of these pressures among the 11 selected lagoons is shown in Table 2, and more details about specific pressures are described below.

Pressures From Agricultural Effluents

Agriculture in the drainage basins along the coast of North Africa is responsible for contaminating lagoons with agrochemicals 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 is from surface and groundwaters that drain from the cultivated areas that cover 78% of the catchment (Damsiri et al., 2015, 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., 2017a). Another Moroccan example of pressures from agrochemicals is an irrigated agricultural area of 92 km² around the Nador lagoon (Re and Sacchi, 2017).

In the case of Algeria, many studies describe the effect of agricultural pollutants and livestock manure (Nadira, 2008) from the two rivers “Rkibet and El Mellah” (Chaoui et al., 2006; Magni et al., 2015) on fish, mollusks, 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 et al., 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).

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, and underwater noise (Table 2).

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 35 m⁻²) on buoys and hulls of vessels (Khedhri et al., 2017b).

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 lagoon (Egypt) exert significant pressures on this ecosystem (i.e., overfishing).

Pressures From Urban and Industrial Effluents

There are three types of effluent affecting lagoons including (i) urban sewage untreated or through a wastewater treatment plants (WWTP); (ii) urban wet weather discharges including rainwater, runoff water, and 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 (Table 1), but there are additional pressures from urban and industrial effluents (Oczkowski et al., 2008; Tlig-Zouari and Maamouri-Mokhtar, 2008; Nassar and Gharib, 2014; Alves Martins et al., 2015; Derradji et al., 2015; Bocci et al., 2016; Dagher et al., 2016; Hammani et al., 2016; El Asri et al., 2017b; El-Zeiny and El-Kafrawy, 2017; Khedhri et al., 2017a).

The increasing tourist development activities around lagoons in North Africa have 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 four 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 (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 14,000 m³, and El Aroui WWTP is a natural lagoon with a treatment capacity of 2,500 m³ per day. These treatment plants are undersized; thus, there are pressures from effluent into the lagoon, as well as anaerobic microbial degradation (Giuliani et al., 2015b). 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 (Giuliani et al., 2015b), and increasing inputs of polybrominated diphenyl ethers (Piazza et al., 2016).

The effluent from industries around Bizerte lagoon (Tunisia) has only primary wastewater treatment (Barhoumi et al., 2014; Hammani et al., 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, 2015) and inadequate sewage treatment due to high tourist influx (Gharib et al., 2011).

Pressures From Civil Engineering Projects

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

Nador lagoon (Morocco) has had a new inlet since 2011 that was made to increase water exchange with the sea (Bocci et al., 2016). Most of the modern centers of Tunis city have 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 2002 shows the pressures of coastal infrastructure and the expansion of the city at the northern and southern limits of the lagoon (Chouari, 2015). 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).

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)

antifouling 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 (Table 2) 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 ES (Newton et al., 2018) and can lead to an impact on human welfare.

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 level. Table 3 shows the state changes in lagoon ecosystems (components and processes), intermediate services (supporting and regulating services), and the final ES (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 ES components, intermediate services, and regulating and supporting services, as well as final ES (El Asri et al., 2017c).

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 et al., 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 ES 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 -7.5 Mm³ of the lagoon’s annual water flowing into the Mediterranean sea (Béjaoui et al., 2017).

The subsidence land rate around Tunis lagoon (Tunisia) is 22 mm year⁻¹, which may lead to state change through marine submersion and flooding hazards (Ennesser et al., 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 wastewater 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 concentrations 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 ES. The provisioning 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 et al., 2017), where symptoms

TABLE 3 | The state change in North African lagoons: “X” represents documented and “?” undocumented state change.

| Countries | Morocco | | | Algeria | Tunisia | | | Libya | Egypt | | |
|--------------------------|--------------|----------|-------|-----------|---------|-------|-----------|-------|---------------|----------|----------|
| | Khenifiss | Oualidia | Nador | El Mellah | Bizerte | Tunis | Boughrara | Farwa | Marsa Matrouh | Burullus | Bardawil |
| State change | | | | | | | | | | | |
| Lagoons 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 |

These are based on Elliott et al. (2017) ES classification.

of microbial anaerobic degradation have been observed from agricultural input (Giuliani et al., 2015a). 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, 2015) and domestic sewage (Gharib et al., 2011) 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 ES 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 2,053.1 tons in 2009 and then decreased to 518.7 tons in 2014, followed by an increase to 1,973.4 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 et al., 2016), which affects nets and netted fish. The armored dinoflagellate *Alexandrium* species, which is a toxic species, now accounts for 17% of total Dinophyceae taxa (El-Kassas et al., 2016).

The environmental state of sediments in Marsa Matrouh lagoon (Egypt) has deteriorated with contamination and pollution from the trace metals vanadium, aluminum, tin, arsenic, and selenium (Abdel, 2015). This deterioration in sediment quality affects the regulating and provisioning final ES; for example, high concentrations of aluminum (100 µg g⁻¹; wet weight) have been observed in the fish *Pagellus erythrinus* and may damage its liver (Abdel, 2015).

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 ES of coastal lagoons may ultimately impact

on human welfare (Table 4). 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 ES. 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 HAB 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 4).

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 is a risk to human health (Giuliani et al., 2015a). The harvesting and selling of oysters from the breeding site of Oualidia lagoon were 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 overenrichment 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 “Marteliosis” that is caused by the protozoan parasite *Marteilia* species has infected *Mytilus*

TABLE 4 | 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 | | |
|--|-----------|----------|-------|-----------|---------|---------|-----------|-------|---------------|----------|----------|
| | Khenifiss | Oualidia | Nador | El Mellah | Bizerte | Tunis | Boughrara | Farwa | Marsa Matrouh | Burullus | Bardawil |
| Impact on human welfare | | | | | | | | | | | |
| Loss of revenue or jobs from declining fish catches | | X | X | X | X | X | | ? | | X | X |
| Loss of revenue or jobs from Harmful Algal Blooms | | | ? | | X | | X | | | X | X |
| Loss of revenue or jobs from pollutants in seafood | X | X | X | X | X | | X | X | | X | |
| Loss of seafood provision or risk to public health from contaminated seafood (toxins or chemicals) | | X | | | X | | | ? | | X | X |
| Risk to public safety due to subsidence, flooding, or storm damage | | | | | | | ? | | ? | X | |

galloprovincialis, which has impacted provisioning services of a commercial species (Elgharsalli et al., 2016). Furthermore, the high concentrations of TBT in seafood, such as commercial species of bivalves (*R. decussatus*, *C. glaucum*, *P. nobilis*, and *M. galloprovincialis*), have 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) have 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 et al., 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, 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., 2016). This impacts the provision of commercial fish species (El-Zeiny and El-Kafrawy, 2017) to people living in the region (Orabi et al., 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 defenses (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 et al., 2016; El-Kassas et al., 2016).

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), because of 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.

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 UWWTP, Moulay Bouselham and Oualidia have one, but Sidi Moussa has none. Morocco also created the National Agency for Aquaculture Development in 2011, which has developed environmental measures that should be followed by the aquaculture industries. The National Agency for Aquaculture Development 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).

Urban WWTP 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 have 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).

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 ES of the lagoons. This can be achieved by policy instruments to protect these ecosystems.

At the national level, Morocco implemented new legislation (Conseil Economique, Social et Environnemental, 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 100 m 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 (Conseil Economique, Social et Environnemental, 2014). Another law that is under development calls for the conservation of fisheries ecosystems and the protection of the marine environment against pollution

(Secrétariat Général du Gouvernement Marocain, 2017). Morocco has created a special planning agency for the Nador Lagoon, the Agence d'Aménagement de la Marchica.

In 2002, Algeria passed legislation (Journal Officiel de la République Algérienne, 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 littoral⁴, 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 socioeconomic 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 (Egyptian Environmental Affairs Agency, 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 (SDGs) 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 SDG 13 "Climate Action."

Options 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 ES (e.g., food).

Once the management options have been identified, these should be checked to see whether they follow the 10-tenet approach (Elliott, 2013; Barnard and Elliott, 2015; Elliott et al., 2017), to be both successful and sustainable. The measures should include both short- and long-term plans that can deliver immediate, positive results, as well as mitigate and prevent future issues. One of the main short-term measures is the construction of UWWTP in some lagoons, for example, Farwa and Ain

Zaina in Libya and 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, for example, Oualidia and Tunis lagoons, and 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 reutilized as a fertilizer for some crops, for example, fruit trees. The use of UWWTP effluent for irrigating lawns and golf courses can improve the sustainability in arid countries.

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, for example, Moulay Bouselham 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, for example, Marsa Matrouh in Egypt and 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 overconstruction and establish setback lines, for example, 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 and hydrological, physiochemical, biological, and ecological aspects of the lagoons, and not focus on only 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, 1,863 students and

⁴http://www.apal.nat.tn/site_web/index.html

professors were introduced to the value of lagoons by this research group⁵.

Conflict management can be improved by organizing a stakeholder forum 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 processes.

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 can lead to new blue economy activities such as bioagriculture, ecotourism, ecological shipping, and organic aquaculture. This could ensure an increase in blue growth related to North African lagoons.

Confusion About Nomenclature of Lagoons in the Context of North African Lagoons

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, and 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 Bouselham and sometimes the term “sebkha.” Others names include “Mar Chica” for Nador lagoon, a remnant of Spanish colonization. In Algeria, “Lac,” which means lake, is used, for example, “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 as Ain Ghazala and El Burdi are coastal inundations.

Knowledge Gaps in North African Lagoons

The analysis carried out in the present study 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; Ramdani et al., 2009b; Thompson et al., 2009; Raji et al., 2018).

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 ES and the impact on human health and human welfare.

CONCLUSION

The information about North African lagoons is diffuse and heterogeneous, and the terminology is often confusing. North African coastal lagoons are complex, social-ecological environments; thus, 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).

The research mapped the existing North African lagoons, and 11 of 21 coastal lagoons were analyzed. 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), and 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, because 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

⁵http://www.grepom.org/wp-content/uploads/Rapport-annuel-_Activité_Centre-Walidia_2017.pdf

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 ES (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 ES 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 and economic services and ES of these important environments. This can foster a more transdisciplinary approach and improve the implementation of policies aimed at coastal protection and improving ES. An investment in sustainable extraction of resources, bioagriculture, 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.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

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AUTHOR CONTRIBUTIONS

All authors helped to shape the research, analysis, and manuscript and provided the critical feedback. All authors discussed the results and contributed to the final version of the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2020.00037/full#supplementary-material>

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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