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Research Article

GIS assessment of shorelines during the last century and their effect on fishing activities in a Mediterranean Lagoon

Abderraouf HZAMI*[1], Oula AMROUNI[1], Sirine ABDELJAOUAD[1,2], Essam HEGGY[3,4], Rimel BENMESSAOUD[2], Gil MAHE[5] & Hechmi MISSAOUI[1]

1 University of Carthage. National Institute of Marine Sciences and Technologies (INSTM), 2025 Tunis. Tunisia.

2 University of Carthage. National Agricultural Institute of Tunisia (INAT), Tunis 1082, Tunisia.

3 University of Southern California. Viterbi School of Engineering, Los Angeles, CA, USA.

4 California Institute of Technology, Jet Propulsion Laboratory, Pasadena, CA, USA.

5 UMR HydroSciences Montpellier, IRD, France.

*__Correspondence__: abderraouf.hzami@instm.rnrt.tn

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Abstract: The Mediterranean region hosts more than 100 coastal lagoons, which play a crucial ecological role and offer vital goods and services for humans. This research focuses on monitoring the shoreline of Ghar El Melh lagoon in the Gulf of Tunis, Tunisia, to assess how environmental changes affect local fishing activities.

The methodology is based on a long-term diachronic study (1881-2021) of the lagoon's shoreline, using the statistical tool DSAS (Digital Shoreline Analysis System) along with a socioeconomic investigation. The fisheries survey responds to requests from regional fisheries authorities, specifically the national fishing and aquaculture department of the Ministry of Agriculture, Water Resources, and Fisheries of the Tunisian Republic. The goal is to collect data that accurately reflects the current state of lagoon fisheries.

The survey was conducted in Ghar El Melh city and involved 34 local lagoon fishermen over a period of one week, from March 20th to March 27th, 2022. The diachronic study revealed that the maximum erosion rate of the lagoon is -14.88 ± 0.20 m/yr in the southeast, while the accretion rate is +7.35 ± 0.20 m/yr in the northeast. The lagoon's surface area expanded by 400.9 hectares between 1881 and 2021, negatively impacting fishing activities and resulting in a 72% decline in annual fishing yield from 1993 to 2022.

Our findings demonstrate the significant impact on the lagoon's sedimentary dynamics, altering water flow patterns and affecting nutrient distribution, sediment deposition, and the transport of larvae and juvenile fish. Additionally, overfishing, along with increasing fishing efforts, accelerates the decline of the fisheries population and the deterioration of ecological conditions within the lagoon.

Keywords: GIS; Lagoon; Socioeconomic; Shoreline; Lagoon fisheries; Sediment dynamics; Coastal erosion; Ghar El Melh; Tunisia.

1. Introduction

Coastal lagoons offer a variety of natural services that are greatly appreciated by society, including fisheries productivity, marine storm protection, tourism, and others. We examine how global climate change can impact physical structure, ecological characteristics, and social values associated with lagoons, particularly along the Mediterranean coast (Gonenç & Wolflin, 2004). Coastal lagoons are shallow bodies of water found along the coast. They are separated from the sea by sand or barrier islands but stay connected to the sea through small openings (Kjerfve, 1994). Coastal lagoons are threatened by natural and anthropogenic factors, including eutrophication (Ben Mustapha et al., 2021), urban flooding, climate change, and changes in water quality (Esteves et al., 2008; Hzami et al., 2025; Khazri et al., 2023).

Therefore, lagoons are one of the most complex and sensitive parts of livelihoods. However, climate change, agriculture, urbanization, and industrialization have put pressure on ecologically and economically important wetlands (Pérez-Ruzafa, 1996; Hzami et al., 2024). Additionally, uncontrolled changes in the size and quality of the lagoon have become a significant issue (El-Asmar et al., 2013). According to Davidson (2014), about 50% of the world's lagoons have disappeared since 1900.

Coastal lagoons cover 13% of the world's coastline, according to Barnes (1980). In the Mediterranean region, over 50 lagoons have been studied for their ecological and hydrological characteristics. In Tunisia, lagoons occupy 19.5% of the country's land surface and are marine habitats with a total surface area of 84407 ha (APAL, 2015). The Lagoon of Ghar El Melh is a vital aquatic ecosystem in northern Tunisia, possessing both ecological and economic significance. This Ramsar wetland provides diverse habitats for migrating fish and birds (Dhib et al., 2017). The decline in biodiversity and fishery resources, as well as the decrease in fishing income, is largely attributed to human activities such as the release of urban and industrial wastewater, drainage system discharges, and fishing operations. The Ghar El Melh lagoon's environment has been altered by natural and anthropogenic factors such as climate change, urbanization, overexploitation of the shoreline, coastal erosion, and pollution (Moussa et al., 2005; Ayache et al., 2009; Saidi et al., 2014; Oueslati et al., 2015; Béjaoui et al., 2018; Hzami et al., 2021; Amrouni et al., 2023). These factors have altered the lagoon's landscape and shoreline, resulting in a decline in agricultural land and an intensification of urban activity (Hzami et al., 2024).

Ghar El Melh Lagoon is a valuable coastal wetland in northern Tunisia, offering a vital ecological, cultural, and socio-economic asset in the Mediterranean region. This is a sedimentary feature formed both by the dynamic freshwater inflows from the Medjerda River and the marine influences from the Mediterranean Sea. The lagoon sustains a diverse ecosystem, supporting migratory birds, endemic fish, and unique flora, including seagrasses and salt marsh vegetation (Ben Mustapha & Amrouni, 2024; Posidonia; IUCN, 2020). Its ecological services, including carbon sequestration (Hammami et al., 2022; Oueslati et al., 2025), water filtration, and coastal erosion mitigation (Makarius & Breil, 2022), ensure the environmental stability across the region. The lagoon's hydrological balance, driven by seasonal freshwater inputs and tidal fluctuations (Moussa et al., 2005), maintains critical habitats that support its ecological resilience.

For centuries, Ghar El Melh has served as an authentic cultural and economic heritage, with artisanal fishing anchoring the livelihoods of local communities (Dhib et al., 2017). Over the last decades, the lagoon has undergone increasing pressures from environmental changes, such as shoreline retreat and rising sea levels (Hzami, 2021; Hzami et al., 2021), alongside human-induced stressors like agricultural runoff (Martínez & Rico, 2022; Ben Ammar et al., 2016), pollution (Sebei et al., 2020), and uncontrolled urban coastal development (Oueslati et al., 2015).

These factors have disrupted the lagoon's ecohydrological dynamics. The lagoon, which has been the subject of several restoration activities, was classified as a UNESCO Ecohydrology Demonstration Site under the Observatory of Medjerda Littoral (OMELI) in 2022 (Elfithri et al., 2025). This distinction shows how water resources can be managed sustainably, while also promoting eco-friendly practices, encouraging eco-tourism, and fostering international cooperation to protect coastal wetlands in the Mediterranean and Africa (Makarius & Breil, 2022).

Previous studies on Mediterranean lagoons have often been limited, focusing mainly on ecological or hydrological changes without considering social and economic impacts, and rarely using long-term data. Only a few studies have examined the combined effects of climate change and human activities on lagoon ecosystems, particularly their impact on small-scale fisheries.

This study addresses these gaps by utilizing geospatial data to develop a new interdisciplinary approach. It examines how natural and human-driven factors influence shoreline changes and ecohydrological processes in the Ghar El Melh coastal lagoon, while also assessing their impact on artisanal fishing and local communities. By providing practical insights for sustainable management and resilience, this research supports broader global efforts to protect coastal wetlands.

The goal of this research is to track changes in Ghar El Melh's shoreline and identify the main environmental and human factors influencing its ecosystem, with a focus on their impact on local fishing and livelihoods. A broader objective is to help develop integrated water management systems for lagoons and coastal areas in the Mediterranean and Africa, leveraging the lagoon's role as a UNESCO ecohydrology demonstration site.

2. Materials and Methods

2.1 Study area

The study area extends along the coast of the Ghar El Melh Lagoon, located Northeast of the Gulf of Tunis between the coordinates 37°06′–37°10′ N latitude and 10°08′–10°15′ E longitude on the eastern coast of the Mediterranean (Figure 1). It is bordered in the north by Djebel Nadhour and in the southwest by the low-lying plain of the Medjerda watershed (Samaali, 2011).

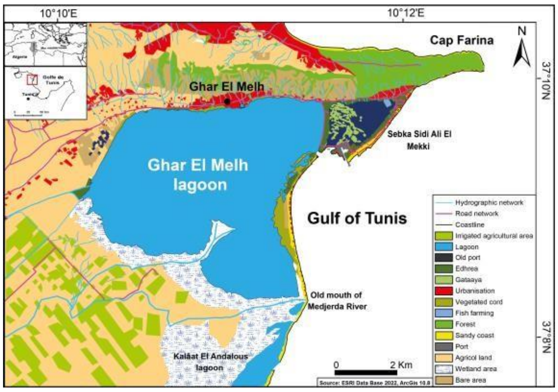

Figure 1. Location of the Ghar El Melh lagoon, Gulf of Tunis, Mediterranean Sea.

According to Ktari-Chakroun et al. 1985, the lagoon's surface covers 3000 ha and is 6.45 km wide and 10.6 km long at its largest. The Ghar El Melh Lagoon is a shallow water bodies (<-1.9 m depth) and quite strongly saline (37 – 42%) due to its broad connection to the sea (El Boughaz) (Romdhane, 1985). This lagoon is characterized by a Mediterranean climate, which belongs to the sub-humid (10%) and upper-semi-arid (90%) bioclimatic zones

(Gounot, 1958). Ghar El Melh's average annual rainfall is 23.5 mm, ranging from 1.7 to 49 mm. The maximum rainfall occurs in autumn, with 56–70 mm recorded in November and December. The region has a Mediterranean climate, with an average temperature of 18–20 °C (OMELI weather station, 2025).

The sedimentary evolution of the Medjerda Delta during the Pliocene period resulted in the accumulation of alluvial deposits in the former Bay of Utique (Delile et al., 2015), leading to the development of the shoreline (Romdhane, 1985). This, in turn, generated the Ghar El Melh lagoon complex. Since the mid-polio-quaternary period, the Medjerda yield has fed the Ghar El Melh Lagoon and the neighboring low-lying areas (Oueslati et al, 2015) until around 1890. At that time, the main course of the Medjerda River slightly diverged south of the lagoon, creating a new estuary that functioned until 1973 (Paskoff, 1994). Two coastal harbors were built on the lagoon of Ghar El Melh. The old fishery port was established in 1638 (Jalloul, 1999), when the lagoon was still an open sea bay (Jauzein, 1971; Slim, 2004). A new fishery port was built in 1974 on the northeastern ridge of the lagoon (Oueslati et al, 2015).

The construction of the Sidi Salem dam on the principal course of the Medjerda River in 1981 disrupted sediment discharge (Ben Moussa et al., 2019). The operation resulted in a reduction in grain size and significantly decreased the amount of sand reaching the coast (Ben Moussa et al., 2019).

As a result, the shoreline of the lagoon has retreated since continental sand is the primary source of sand for the shore (Hzami et al., 2021). The Ghar El Melh lagoon's high coastal vulnerability is primarily due to both the deficit in natural sand recharge and rapid urbanization over the past few decades (Hzami et al., 2024). In 2023, the population density was approximately 215.5 people per sq. km, with 46% attributable to urban growth (INS, 2024).

The ecological health of the lagoon is threatened due to changes in the lagoon’s hydrodynamics, water balance, sedimentation, and water quality deterioration (Moussa et al., 2005, and Béjaoui et al., 2018; Ben Mustapha et al, 2023).

The Ghar El Melh lagoon is currently facing a decline in species diversity and fishery resources because of domestic and industrial wastewater discharges, drainage system outflows, and fishing activities. Historically, this ecosystem supported a rich fish community of about 45 species and was especially valued for its commercially important fish like grey mullets (*Mugil cephalus*, *Chelon spp*.), European eel (*Anguilla anguilla*), sea bass (*Dicentrarchus labrax*), and sole (*Solea spp*), along with cephalopods such as *cuttlefish* and *octopus* (Kraïem et al., 2009). Fishery yields, which amount to approximately 80 tons annually, have mainly consisted of grey mullet and eels. However, recent research shows these resources are increasingly threatened by human impacts (Kraïem et al., 2009). This has resulted in a decline in fishing revenues from the lagoon (Moussa et al., 2005).

2.2 Diachronic analysis of the shoreline changes

We utilize the Digital Shoreline Analysis System (DSAS) method, as detailed in Thieler et al. (2009), for long-term shoreline monitoring. For this purpose, we have gathered data from a variety of sources, including Landsat (1972), Spot (1988, 1999, and 2012), Sentinel 2A (2016) datasets, aerial photography (1974), topographic maps (1936), and marine maps (1882) (Table 1).

Table 1. Data used for the diachronic shoreline analysis of the Ghar El Melh lagoon, Gulf of Tunis, Tunisia, Mediterranean.

Spatial database	Date (Scale)	Resolution (m)	Sources
Topographic maps	1936 (1/50000)	2	Tunisian Office (OTC) Tunisian National Office of Mines (ONM)
	1974 (1/25000)		
Bathymetric map	1881 (1/100000)	4	
Geological map	1948 (1/50000)	2	
Satellite imagery	Landsat (1972)	30	https://earthexplorer.usgs.gov//
	Landsat (2010)	30	
	Spot 1 (1988)	20	
	Spot 4 (1999)	20	
	Spot 5 (2012)	5	
	Sentinel 2A (2021)	10	

The cross-shore transects extending 1000 meters are employed to quantify shoreline variations along the Ghar El Melh lagoon coastline (Figure 2). The calculated shoreline retreat rate was used to generate a temporal series that is incorporated into Geographic Information Systems (GIS).

Through these temporal series, the evolution of shoreline geometry and positions over the past century can be observed. In our analysis, we relied on two statistical outputs derived from the Digital Shoreline Analysis System (DSAS) model: (1) the Net Shoreline Movement (NSM), which quantifies the total displacement between shoreline positions recorded in 1881 and those in 2021; and (2) the End Point Rate (EPR), which provides an estimate of the annual shoreline retreat rate. For this study, errors were quantified using algorithms developed by Van der Wal and Pye (2003) to assess the rates of shoreline change.

Furthermore, we adopted a margin of error based on the signal-to-noise (S/N) ratio assumptions proposed by Dolan et al. (1980) and Thieler et al. (2009), applicable to both NSM and EPR measurements.

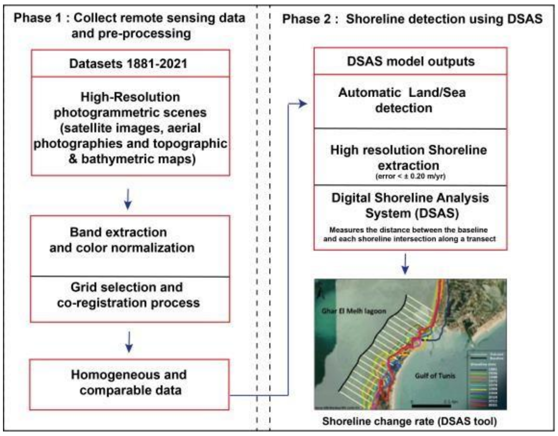

Figure 2. Workflow for statistical analysis with Digital Shoreline Analysis System (DSAS).

2.3 Monitoring the fishing activity

The fisheries survey proposed in this study was designed in response to requests from regional fisheries authorities (National Fishing and Aquaculture Direction of the Ministry of Agriculture, Water Resources, and Fisheries of the Tunisian Republic). Its objective was to support the collection of a dataset that accurately reflects both the current status and the anticipated trends of lagoon fisheries. The survey involved approximately 34 native lagoon fishermen from Ghar El Melh city, conducted in March 2022. Fieldwork generally took place during regular working hours (9:00 a.m. to 5:00 p.m.); however, on certain occasions, survey teams adjusted their schedules to start earlier or finish later in order to meet the daily target of fishermen assigned for interviews.

The survey was conducted using socioeconomic questionnaires adapted from the "*Socioeconomic fisheries: A manual for the collection of a minimum dataset*" (Kronen et al., 2007). This manual is intended for fisheries managers, research institutions, non-governmental organizations, universities, regional and international organizations, as well as practitioners involved in the collection, analysis, development, implementation, *and monitoring of coastal fisheries* management strategies or measures.

It recommends the use of fully structured questionnaire surveys, considered the most efficient and effective approach in terms of time, finances, and human resources. Guided by this framework, we designed a questionnaire structured into four main sections to collect the required data.

The first section of the questionnaire focused on socio-demographic characteristics of the respondents, including age, educational background, household size, and other relevant personal attributes. The second section addressed fishing activities, encompassing fishing effort, fleet composition, types of fishing gear, and the spatial distribution of fishing grounds (Figure 3). The third section was dedicated to catch data, detailing species composition, landed quantities (in kg), and corresponding economic values (in $). This section also included information on fishing-related costs, such as capital investment and operational expenses, as well as the economic returns generated from the fishing activities.

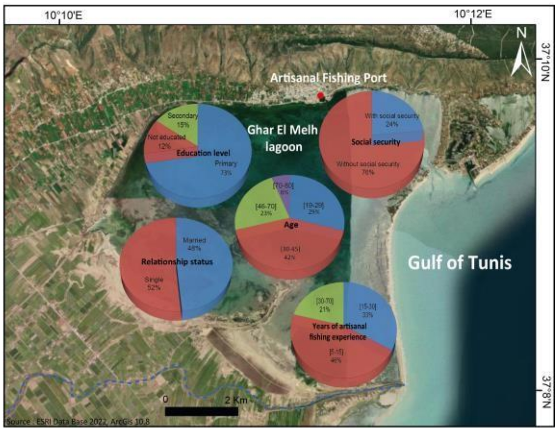

Figure 3. Collected information related to the social aspects of artisanal fishermen of Ghar El Melh lagoon, Gulf of Tunis, Tunisia, Mediterranean.

The fourth section of the questionnaire addressed the effects of spatiotemporal changes in the lagoon geomorphology and sedimentation on fishing activities.

To support this analysis, maps featuring a geo-referenced segmented grid were provided. Respondents were asked to delineate the boundaries of their fishing grounds according to the season and type of fishing gear used. The landing value of each species for each monitored vessel was calculated following the method described by Dang. (2020), as illustrated in Table 2.

Table 2. Economic value of fishing services of the lagoon of Ghar El Melh, Tunisia (2022).

Economic value of fishing services	Equations
Landing value ($/yr)	[Annual quantities caught (kg/yr) x Average selling price ($/kg)] (1)
Total landing value ($/yr)	Σ Landing value ($/yr) (2)
Net Production value or the landing	Total Production Value ($/yr) - Total costs ($/yr) (3)
Economic value of the landing per fisherman ($/yr)	Total net landing value ($/yr) ÷ Number of Respondents (4)
Economic value of the fishing service ($/yr)	Economic value per fisherman ($/yr) * number of active total fishermen (5)

When conducting sample surveys to assess the status of fisheries, it is important to note that the estimated values (e.g., revenue and catches) may not perfectly reflect the actual values. The discrepancies between the estimates and the real/actual values are referred to as sampling errors.

These differences are called sampling errors. Generally, larger sample sizes result in fewer sampling errors and more precise estimates of fishery status. It is worth noting that estimates based solely on Ghar El Melh are likely to contain greater errors compared to those derived from the entire fishery since the latter includes all samples.

Moreover, survey results are always subject to a degree of uncertainty, not only because they only involve a subset of the population but also due to potential measurement errors. This uncertainty can be mitigated by increasing sample size and improving measurement instruments.

3. Results and discussion

3.1. Long-term shoreline change

Figure 4 and Table 3 show how the lagoon shoreline has changed over the past 140 years (1881-2021). We used the classification of shoreline trends from Esteves and Finkl (1998) to classify the data. The accretion rate corresponds to shoreline change rates exceeding +0.5 m/yr, while erosion rates are distinguished by change rates ranging from -1 to -5 m/yr. The Net Shoreline Movement (NSM) and End Point Rate (EPR) reveal that the southern part of the lagoon, particularly near the old Medjerda Delta area, has been most affected by erosion. Between 1881 and 2021, the maximum shoreline retreat rate reached -14.88 ±0.20 m/yr (Table 3). On the Boughaz channel, the End Point Rate (EPR) values showed an increase rate of +7.35 ±0.20 m/yr, which was attributed to the accumulation of sediment along the lagoon's northwestern ridges (Amrouni et al., 2023). In the northwestern sector, the shoreline was relatively stable, with an EPR rate of -0.05 ±0.20 m/yr, as the lagoon inclined naturally toward Djbel Nadhour (Figure 3).

Between 1881 and 1936, the eastern part of the lagoon experienced natural accretion, with rates ranging from +21.1 ±0.23 m/yr to +40.05 ±0.12 m/yr (Figure 4; Table 3). This positive pattern indicates the significant sedimentation input from the Medjerda River to the local sediment budget prior to the construction of the new port in 1974 (Moussa et al., 2005).

Erosion rate varied considerably between 1988 and 2021, on the western shoreline, with retreat rates ranging from -0.35 ±0.17m/yr to -38.06 ±0.12 m/yr (Table 3). As a result of these extreme erosion rates (<-5 m/yr), 40.4 ha of agricultural land, including Ramli crops, was submerged. The marine intrusion into these cultivated areas became more pronounced after 2015 (Oueslati et al., 2015).

Land-use changes also contributed to the lagoon's evolution. According to Hzami et al. (2024), between 1985 and 2021, agricultural land decreased by 5%, while urban areas increased by 8%. During this period, the region experiences intense tourism pressure, with more than 30,000 daily visitors to the sandy barrier of Ghar El Melh (Mzita, 2024), and an accelerated erosion rate along the western fringe, reaching a maximum of -38 ±0.12 m/yr (Figure 3).

The spatial evolution of the lagoon revealed an overall increase in surface area from 2,800.5 ha in 1881 to 3,300.4 ha in 2021 (Figure 4). Between 1881 and 1972, the lagoon expanded from 2,800.5 ha to 2,900.2 ha, followed by a slight decrease to 2,900.1 ha in 1974, coinciding with the construction of the new port. The net increase of 400.9 ha between 1881 and 2021 confirmed the occurrence of severe shoreline erosion, with retreat rates between -1 and -3 m/yr, which reshaped the lagoon's morphology.

Similar shoreline retreat rate phenomena were also observed in other Mediterranean lagoons. In particular, the Venice lagoon (Italy) and the Amvrakikos Gulf lagoon complex (Northern Greece) experienced comparable erosion processes driven by the combined effects of human intervention and climate change (Zaggia et al., 2017).

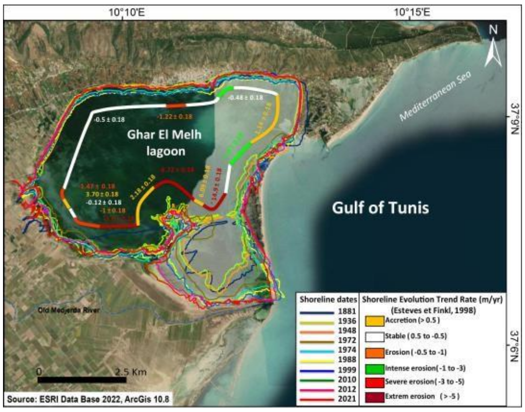

Figure 4. Map synthesizing the shoreline movement trend at the coast of the Gulf of Tunis during the 1881−2021 period.

Table 3. Statistical analysis of the shoreline evolution of the Ghar El Melh lagoon over the period of (1881–2021); End Point Rate (EPR); Net Shoreline Movement (NSM). Negative value is for erosion rate.

Study site (3000 ha)	Date (yr)	EPR Max (m/yr)	EPR Min (m/yr)	EPR Average (m/yr)	Error EPR (m/yr)	NSM Max (m)	NSM Min (m)	NSM Average (m)	Error NSM (m)
Ghar El Melh lagoon	**1881-2021**	-14.88	+7.35	-1.30	± 0.20	963.09	-172	-1530	± 28
	1881-1936	-29.32	+21.30	-1.34	± 0.23	1171	-74	-1612	± 12.63
	1936-1988	-24.58	+20.90	-0.35	± 0.17	1086	-19.19	-1278	± 8.84
	1988-2021	-38.06	+40.05	-2.63	± 0.12	1321	-86.81	-1256	± 3.96

3.2. Impact of geomorphological changes on lagoon fishing activity

Researchers interviewed 34 fishermen as part of this study. Eighty percent of them reported that fishing grounds and fisheries resources were threatened over the past decade, with potential long-term repercussions. The other respondents forecasted the extinction of specific resources within the next 10 to 20 years, citing environmental changes that worsen with climate change.

The diversion of the Medjerda course has resulted in a water shortage, diminished freshwater availability, and an increase in organic matter. These modifications have impacted biodiversity within the lagoon. Interviewees identified silting, the relocation of the old Boughaz Channel, and the widening of the new pass as significant challenges for lagoon fishermen. They employ various fishing equipment, including longlines, nets (gillnets, trammel nets), and crab traps. A map illustrating these fishing gears demonstrated overlapping regions (Figure 5).

The practice of installing eel traps in the Ghar El Melh lagoon resulted in significant challenges for fishers using nets and longlines. Due to their strategic placement, these traps intercepted resources before they reached other fishing gear, thereby reducing the productivity and profitability of alternative methods.

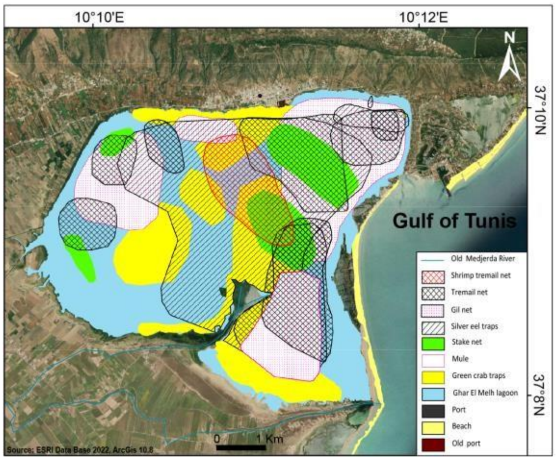

Figure 5. Distribution of fishing gear in Ghar El Melh lagoon, Gulf of Tunis, Mediterranean (2022).

The study's findings demonstrated that both natural and anthropogenic factors drove shoreline changes in the Ghar El Melh lagoon. Natural influences, such as climate change and sea-level rise, directly and indirectly contributed to marine submersion and coastal erosion (Amrouni et al., 2023). At the same time, the diversion of the Medjerda River resulted in a water balance deficit and reduced freshwater inflow, accompanied by an enrichment of organic matter. These hydrological changes altered the lagoon's richness and ecological dynamics.

Interviews with local fishers further highlighted the main challenges they faced, including siltation, the relocation of the old Boughaz Channel, and the widening of the new pass. Fishers reported using a range of gears, such as longlines, combined nets, gillnets, trammel nets, fyke nets, and crab traps. Spatial mapping of these implements (Figure 5) revealed overlapping fishing areas, intensifying competition. Notably, eel traps extended into the lagoon even outside the fishing season, exacerbating conflicts with net and longline users.

Overall, the evidence showed that both natural and human-driven processes influenced the lagoon's spatial and temporal changes. Natural factors, especially sea-level rise associated with climate change, led to marine flooding and increased coastal erosion. Meanwhile, human activities such as river course diversion, infrastructure modifications, and intensive fishing practices further disturbed the ecosystem balance and the sustainability of fishing.

As agricultural land is lost, some farmers are turning to fishing as an alternative means of making a living. However, this shift has increased the pressure on lagoon resources, led to more competition among fishers, and raised concerns about the long-term health of fisheries. It has also highlighted the vulnerability of local communities when their livelihoods depend on the delicate balance between land and water ecosystems. Additionally, increasing water temperatures have altered the lagoon's physical and chemical properties, leading to eutrophication (Zhao et al., 2022). Dumping urban waste directly into the lagoon increases eutrophication, causing anoxic conditions that trigger rapid, short-term drops in lagoon resources. The decline in shrimp populations exemplifies the loss of aquatic biodiversity (Dhib, 2015). This pattern increases pressure on aquatic resources already affected by fishing, risking the survival of certain species, especially those vulnerable to water temperature changes.

Moreover, this phenomenon can also lead to the long-term extinction of fisheries resources. The results of our survey confirm this trend. We observed a decline in landed productivity, from 180 t in 1993 (Moussa et al., 2005) to 50 t in 2022 (Figure 6). Regarding anthropogenic factors, they were linked to population growth, which manifests itself through various consequences, including discharges from dwellings and industries surrounding the lagoon. These discharges saturated the wetland and increased the effect of eutrophication (Fathalli & Amrouni, 2025), and hence, a depression of fisheries resources.

Urban expansion has also contributed to the silting of the Boughaz channel, particularly during storm surge. This has narrowed its depth and length, leading to a loss of lagoon resources to the sea. To compensate for this decline, fishers have intensified their activities, increasing both the frequency of their trips and the hours they spend fishing. The time they spend fishing has grown from 2-4 hours, 15 years ago, to 12 hours by 2022. At the same time, silted areas of the lagoon have made some fishing spots less accessible, reducing the available fishing areas. The increased fishing activities have led to overexploitation of resources and raised serious concerns about the long-term sustainability of the lagoon's fisheries.

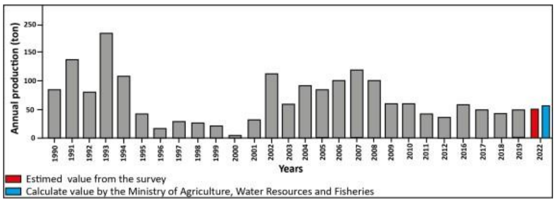

Figure 6. Total fisheries production in the Ghar El Melh lagoon, Gulf of Tunis, Mediterranean.

Analysis of fisheries landing trends in Ghar El Melh Lagoon (Figure 6) shows non-linear dynamics from 1990 to 2022. A slight recovery from 2002 to 2010 (100–120 tons) may have resulted from improvements in water quality or reduced fishing, but the system remained vulnerable. The landings trend decreased from 2011 to 2016, within a production range of 70-80 tons, likely due to eutrophication, siltation, and urban impacts. The drop to 50 tons by 2022 highlights the cumulative impact of ecosystem stressors. These changes underscore the importance of considering both short-term variability and long-term pressures in assessing the sustainability of lagoon fisheries.

3.3. Economic value of fishing activities in Ghar El Melh Lagoon

In 2022, the Ghar El Melh lagoon supported 125 active fishermen, each landing an average of 400 kg per year, resulting in a total catch of 55.1 tons. The average annual landing value per fisherman was estimated at $4,000 per year (Table 4). While this provides a significant income source for local communities, the relatively high fishing effort raises concerns about the sustainability of these resources, emphasizing the need for management measures to preserve both economic benefits and ecological balance.

Table 4. Economic value of lagoon fishing in Ghar El Melh (March 2022), Gulf of Tunis, Tunisia, Mediterranean.

Types	Values
Quantity landed/yr/fisherman	400 Kg
Production value/yr/fisherman	$4000
Total costs/yr/fisherman	$2150
Net value of production/fisherman	$1850
Total value of production (125 fishermen)	$500000
Total costs (125 fishermen)	$268750
Economic value of fishing in the lagoon	$231250

Researchers estimated the average annual cost per fisherman to be $2,150. This figure includes expenses for buying new fishing gear, maintaining the set net, and repairing nets damaged by crab depredation. By multiplying the average landing value by the total number of lagoon fishermen (125), the total annual landing value came out to $500000 per year. The estimated total annual costs for all fishermen were $268,750 per year. By subtracting the total annual cost of fishing activities from the total value of the lagoon's fish catch, we found that the net economic value of these activities was approximately $231250 per year. In 2022, the Ministry of Agriculture, Water Resources, and Fisheries estimated the economic value of the Ghar El Melh lagoon to be $222415.89 for a total catch of 55,915 tons. Despite increased fishing effort and larger fleets in recent years, the total catch in the lagoon has declined slightly, from 200 tons in 1993 (Moussa et al., 2005) to 55 tons in 2022. This decline is likely due to global changes affecting the entire Ghar El Melh lagoon ecosystem. Furthermore, rising water levels and stronger currents, especially since the expansion of the Boughaz channel, have exacerbated the situation by allowing fish to escape from the lagoon into the sea, particularly during marine storm events.

In 1996, an urgent dredging operation was conducted at Boughaz, the only link between the lagoon and the sea (Moussa et al., 2005). As a result, the production of fisheries in this environment plummeted from 200 tons in 1993 to just 26 tons in 1996 (Figure 6). Although the operation enhanced the water circulation and quality in the lagoon, ultimately benefiting fishery production, it failed to restore the environment's original ecological balance. On the other hand, illicit fishing practices, such as installing fixed barriers to catch eels year-round near the lagoon and at the Boughaz channel, have led to the overexploitation of all resources and the capture of specimens under the regulatory size. The decline in fishing economic value will further exacerbate the socioeconomic vulnerability of the coastal lagoon, already classified as highly vulnerable (Hzami et al., 2023).

4. Conclusion

The long-term analysis of shoreline evolution in Ghar El Melh lagoon was conducted across various years, specifically in 1881, 1936, 1948, 1972, 1974, 1988, 1999, 2012, and 2021. Monitoring results indicated that approximately 57.78% of the lagoon's overall shoreline is experiencing erosion rates exceeding -0.5 meters per year. Conversely, 18.33% remains relatively stable, with changes between -0.5 and 0.5 meters, while 23.89% exhibits accretion rates exceeding +0.5 meters per year. The statistical data reveal significant shoreline retreat from 1881 to 1936, with a maximum Net Shoreline Movement (NSM) of -1612 ±6 meters, and notable erosion rates from 1988 to 2021, reaching a maximum Erosion Potential Rate (EPR) of -38.06 ±0.12 meters per year in the southeastern region of Ghar El Melh lagoon. This regression trend has been attributed to the influence of hydraulic structures, such as dams and reservoirs, and the maritime management implemented since 1936 in the lower Medjerda valley and along the northern coast of the lagoon. The study of how these changes have impacted fishing activities indicates that, due to shoreline retreat and natural resource scarcity, fishermen have been compelled to intensify their operations, specifically by increasing the number of sea trips and expanding the fleet size within the lagoon to mitigate economic losses. Nevertheless, such adaptations raise concerns about the sustainability of the lagoon's fisheries sector. It is therefore advisable that all stakeholders in this coastal region collaborate to enhance conservation efforts and mitigate their vulnerability to ongoing coastal changes. This initiative is exemplified by the recent implementation of the OMELI coastal observatory of Ghar El Melh lagoon, which has been designated as an official demonstration site under the UNESCO IHP (Intergovernmental Hydrological Program) Ecohydrology initiative (INSTM, 2023).

Author Contributions

Conceptualization, Abderraouf Hzami & Oula Amrouni; methodology, Abderraouf Hzami, Oula Amrouni, and Essam Heggy; writing original draft preparation: Abderraouf Hzami and Oula Amrouni, data acquisition, and analysis: Abderraouf Hzami, Sirine Abdeljaouad, and Rimel Benmessoud; writing review and editing, Abderraouf Hzami, Oula Amrouni, and Essam Heggy; supervision, Oula Amrouni; project administration, Hechmi Missaoui; funding acquisition, Gil Mahé & Essam Heggy. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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