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ORIGINAL ARTICLE

Assessing the spatiotemporal transformation of a coastal lagoon inlet (1984–2019) using remote sensing and GIS: a study of Khenifiss Lagoon in Southern Morocco

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Abstract
Coastal lagoons are highly dynamic ecosystems that are continually changing in shape and size due to natural processes. This study used satellite imagery, remote sensing, and GIS mapping, along with historical wind and wave data, to comprehensively explore the long-term changes occurring at the Khenifiss Lagoon entrance and its downstream main channel, which is one of the most important wetlands protected by the Ramsar Convention in Morocco. By employing thorough image selection, rigorous corrections, and intricate processing and analysis techniques, this research shed light on the evolution of sediment deposition areas, eroded zones, vegetation coverage, and locations, where dune influence affected sedimentation in this dynamic coastal ecosystem. The investigation spanned from 1984 to 2019 and relied on the analysis of Landsat optical images gathered in 1984, 1990, 2000, 2009, and 2019. During the study period, the entrance to the Khenifiss Lagoon (Foum Agouitir) gradually enlarged, increasing from 1450 m in 1984 to 1650 m in 2019. Concurrently, vegetation coverage within the lagoon's entrance and main channel increased from 53.54 hectares in 2009 to 103.9 hectares in 2019, resulting in a significant decrease in total water body extent. Sediment deposition impacts 206 hectares, considerably surpassing the erosion-affected area of 99.14 hectares. This significant difference emphasizes the rising dominance of sedimentation over erosion at the Khenifiss Lagoon entrance zone. The processes of sedimentation within the lagoon are largely influenced by the dune's advance, which has resulted in silt deposition over an area of approximately 57.39 hectares. These findings highlight the lagoon's exposure to progressive closure and strongly support the need to start a monitoring program to evaluate the lagoon's changing condition, especially at the entrance and the main channel. This study puts forth several recommendations for implementing management strategies aimed at ensuring the sustainability of this coastal ecosystem.

Keywords Coastal lagoon · Spatiotemporal evolution · Khenifiss Lagoon · Remote sensing · GIS

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Introduction

Coastal lagoons cover approximately 13% of the world's coastlines (Barnes 1980), and they are aquatic ecosystems characterized by their shallow nature and their proximity to the marine environment, separated from the open sea by a barrier, land spit, or similar land feature, and connected to the sea through one or more inlets (Pérez-Ruzafa et al. 2011, 2019). Coastal lagoons are highly dynamic ecosystems that are continually changing in shape and size due to natural processes (De Wit 2011). These ecosystems are also known for their high productivity and biodiversity (Lewison et al. 2016). Coastal lagoons, on the other hand, are vulnerable to a variety of pressures and are classified as threatened ecosystems due to a combination of natural and human factors (Mahapatro et al. 2013). Given their substantial socioeconomic and environmental importance, effective management practices are imperative to ensure the preservation and sustainable utilization of these valuable coastal ecosystems (Pérez-Ruzafa et al. 2019). Remote sensing and Geographic Information Systems (GIS) prove to be practical and attractive tools for conducting research and managing coastal ecosystems, encompassing wetlands, estuaries, and coral reefs (Ahmed et al. 2009; Klemas 2011). Common applications of remote sensing in coastal areas include mapping nearshore and shallow marine ecosystems, tracking temporal changes, creating bathymetric maps, and investigating suspended sediment plumes and coastal currents (Green et al. 1996). Nonetheless, the efficacy of remote sensing in the management of coastal zones is compromised by variables affecting data accessibility, such as cloud cover and sensor limitations (Green et al. 1996).

The Khenifiss Lagoon (or "Khnifiss Lagoon" in literature), located in southern Morocco's coastal Sahara, is the largest lagoon and most significant wetland in the Atlantic Moroccan desert. It stands out for its shallow and small basin, with occasional freshwater input from the temporary river known as Oued Aouedri (Dakki and De Ligny 1988; Nogueira et al. 2022). The lagoon is complemented by its uninterrupted connection to the Atlantic Ocean through the only inlet, the Foum Agoutir inlet (Dakki and De Ligny 1988). The lagoon is distinguished by its abundant biodiversity and elevated biological productivity, serving as a crucial wintering habitat for migratory birds. In addition, it provides a habitat for species that are vulnerable or endangered on both national and international levels (Department of Water and Forestry 2008). Since 1983, the lagoon has been protected under the Ramsar Convention (Convention on the Conservation of Wetlands of International Importance) as an important stopover and wintering ground for migratory birds. Besides, it has been designated as a national park since 2006.

The Khenifiss Lagoon serves as a pivotal center for various socioeconomic activities, notably fishing, and employing small fishing boats (El Mahrad et al. 2020). Tourism activities and salt mining further contribute to the lagoon's economic vitality (El Mahrad et al. 2020). The local socioeconomic structure is rooted in fishing and shellfish harvesting, providing a significant source of income and employment (El Mahrad et al. 2020). There are 12 traditional fishing boats, also used for transporting tourists within the lagoon. Recently, the unique ecosystem of Khenifiss has attracted private investors, prompting their involvement in aquaculture activities (Abioui et al. 2018).

The adjacent salt flat, Sebkha of Tarza, spans 830 hectares south of the lagoon and plays a pivotal economic role. Approximately, 418 hectares of salt deposits were exploited by seven small companies (Department of Water and Forestry 2008). These salt pans, serving as substantial artificial salt production sites, yield over 20,000 tons of salt annually, according to the Regional Planning Department of Laayoune in 2022. Moreover, the Khenifiss Lagoon stands out as a site tourist attraction, offering diverse activities like geotourism, ecotourism, bird watching, and nature observation (Department of Water and Forestry 2008).

However, the lagoon has faced significant environmental challenges in recent years as a result of natural and human factors (El Mahrad et al. 2020; Mejjad et al. 2020). These challenges include the migration of transverse sand dunes affecting the lagoon and its inlet (Saltani et al. 2015), the presence of a huge shipwreck obstructing the only entrance (Ministry of Equipment and Transport 2010), and the emergence of new islands in the lagoon's main channel, all of which contribute to a significant sedimentation problem (Amimi et al. 2021). Given these circumstances, the main objective of this study is to identify and assess changes in the lagoon entrance over the last four decades. The primary focus is on assessing changes in sediment deposition areas, vegetation coverage, eroded zones, and locations, where dune influence affected sedimentation throughout the study period. The investigation spanned from 1984 to 2019 and relied on the analysis of Landsat optical images gathered in 1984, 1990, 2000, 2009, and 2019. The time interval between these data points allowed for a thorough understanding of the evolution of sediment-related processes over the study period in this dynamic coastal ecosystem.

The subsequent evaluation of these major entities required a multifaceted approach. The collected satellite images were subjected to a rigorous correction process that included atmospheric, radiometric, and geometric corrections, as well as noise reduction techniques. We utilized the GIS software ArcMap 10.3 to create various false-color composites for each image, enhancing the visibility and contrast of different elements, and we used the Normalized Difference Vegetation Index (NDVI) and the Normalized Water Difference Index (NDWI) to differentiate various features within the study area. Furthermore, we used supervised classification to improve the accuracy of our land cover identification process. Finally, we applied on-screen digitization techniques to map the identified features accurately. This intricate methodology provided a reliable method for distinguishing and quantifying the changes of distinct elements within the satellite images. This study also sheds light on the characteristics of wind and wave conditions in the study area, as well as their impact on the lagoon's dynamics, contributing to a better understanding of the changes that have occurred at the lagoon's entrance. Through a meticulous four-decade analysis of satellite imagery, this study provides valuable insights into the evolving dynamics of the Khenifiss Lagoon, particularly the inlet and the downstream part of the main channel, which are vital for the lagoon's ecosystem survival. It enables us to detect long-term changes, evaluate sedimentation patterns, monitor vegetation coverage, comprehend erosion patterns, and assess the impact of sand dunes. These findings contribute to a better understanding of the evolving features of Khenifiss Lagoon and provide valuable methodology and insights applicable to the management and conservation of coastal ecosystems worldwide.

Study area

The Khenifiss Lagoon, also referred to "Naïla Lagoon" by the local population, depicted in Fig. 1, is a Saharan wetland area that spans an area of 65 km^2. It is the largest Atlantic lagoon in Morocco. It is situated in the southwest of the Moroccan Sahara, between the cities of Tan-Tan and Tarfaya, at a latitude of 28° 03' North and a longitude of 12° 15' West (Hammada 2007). The lagoon is separated from the Atlantic Ocean by a dune barrier interrupted by an inlet known as "Foum Agouitir" (Beaubrun 1976). This inlet, which allows the lagoon to connect with the ocean, is about a hundred meters wide and 5–6 m deep (Beaubrun 1976).

The hydrology of the lagoon is predominantly influenced by tidal dynamics, with tides reaching the bottom of the salt flat Sebkha of Tarza during spring tides (Beaubrun 1976; El Agbani et al. 1988; Lakhdar Idrissi et al. 2004). Indeed, the contributions of freshwater from the continent, especially through the Ouedri River, are minimal (Lakhdar Idrissi et al. 2000). The lagoon's main channel extends for approximately 24 km (Lakhdar Idrissi et al. 2000, 2004) and is bounded by a cliff to the east and active sand dunes to the west, as shown in Fig. 1d. The main channel ends in the southwest with the

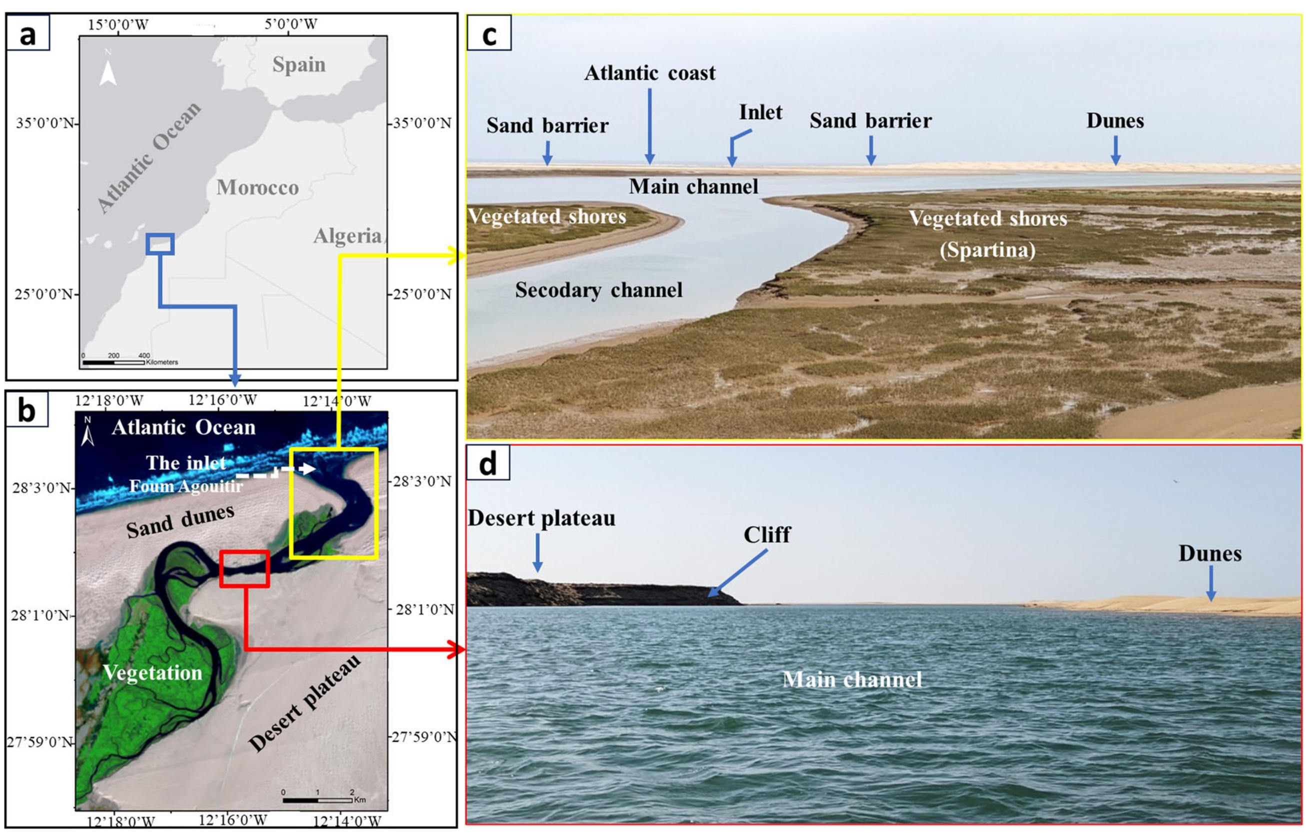

Fig. 1 **a** Geographic location of the study area. **b** True color satellite image of the Khenifiss Lagoon (Landsat 8 OLI image captured on December 14, 2019). **c** and **d** Pictures illustrating the main entities of the lagoon's downstream area, including the main pass (taken in February 2022)

saline depression (Sebkha of Tarza), which is 9 km long and 5 km wide (Beaubrun 1976; Lakhdar Idrissi et al. 2000, 2004). It is bounded to the west by the Hassi Fleiga sand dunes and to the east and south by a high cliff that ranges in height from 22 to 35 m (Beaubrun 1976). This salt flat is submerged by seawater at high tide, especially during spring tides, and as a result of intense evaporation, it produces a sizeable salt deposit (Beaubrun 1976).

Beaubrun (1976) divided the main channel into three parts: The downstream part, stretching over 7 km, is the deepest (6–15 m) and has a sandy bottom and muddy tidal zone. At low tide, some sandbanks emerge. The middle section, 4 km long and 3–4 m deep, has a sandy bottom, and its shores are adjacent to sand dunes. The upstream part, 9 km long, flows into Sebkha of Tarza. Its depth varies from 0.20 to 5 m.

The lagoon is situated within the Saharan bioclimatic zone, and its climate is significantly shaped by the maritime trade winds, leading to elevated humidity levels, substantial cloud cover, and mild temperatures (André et al.1975). The prevailing winds typically blow from the NNW to NE direction (Elbelrhiti et al. 2008). Wind speed over the past three decades has varied between 2 and 14 m/s (Adnani et al. 2018). Temperature fluctuations are strongly affected by the thermal conditions of coastal waters, with temperatures ranging from a minimum of 12 °C to a maximum temperature of 29 °C (Adnani et al. 2018). The highest temperatures are typically registered during September and October. Monthly average precipitation is very low (164 mm annually over the last three decades) and highly irregular (Adnani et al. 2018).

In the Khenifiss Lagoon, three main morphological lagoon features are observed, namely, the sandy barrier formed by the Hassi Fleiga dunes, the Foum Agouitir inlet ensuring the connection with the ocean, and a water depression containing a main channel. According to Postma's classification (1969), this lagoon belongs to the anti-estuarine type. It is situated in a mesotidal environment, according to Hayes' classification (1975), and is partially enclosed, according to Nichols and Allen's classification (1981). Furthermore, it is considered a lagoon with restricted exchange with the ocean, following Kjerve's classification (1986).

The sedimentology of the lagoon is characterized by three main sediment types: sandy, muddy-sandy, and sandy-muddy (Lakhdar Idrissi et al. 2000). Sandy mud constitutes the majority of deposits, mainly located along the left bank of the downstream area and the marshes of the upstream zone (Lakhdar Idrissi et al. 2000). These areas exhibit low hydrodynamic activity, facilitating sediment retention due to the presence of seagrasses and resulting in the accumulation of organic matter. In contrast, at the channel and pass levels, sediments are primarily sandy, marked by intense turbulence and a low organic matter content (Lakhdar Idrissi et al. 2000).

From a geological perspective, the Khenifiss Lagoon is located in the northern part of the Tarfaya-Laâyoune Coastal Basin (Dakki and De Ligny 1988). This geological basin comprises a Precambrian basement, which outcrops in the Saharan hinterland, while a Mesozoic-Cenozoic coastal sedimentary cover predominates (Abioui et al. 2019). This cover includes Miocene sands overlaid by a Quaternary Moghrebian slab mainly composed of sandstone and limestone (Ranke et al. 1982; Dakki and De Ligny 1988). The thickness of the Quaternary platform, where the Khenifiss Lagoon is situated, can reach several meters, up to 40 m (Dakki and De Ligny 1988).

Coastal lagoons are ephemeral coastal features, having a recent origin, and their evolution occurs rapidly on a geological timescale (Kjerfve 1986). Research into the formation of coastal lagoon systems along the Moroccan Atlantic coast has revealed that the emergence of these systems can be traced back to the eustatic rise in sea levels during the Holocene (Carruesco 1998). This rise has resulted in marine submersion, concurrently giving rise to the formation of barriers along both straight and indented coastlines (Bird 1994).

Materials and methods

Remote sensing and GIS mapping

The GIS is a tool that facilitates the acquisition of high-quality and current information to assist in gaining a deeper understanding of the operations within coastal zones (Burrough et al. 2015; Nakhli and Ghazi 2008). It can be succinctly described as a compilation of geographical data managed by a unified system, aiming to improve the comprehension and meaningful incorporation of the dynamics of natural phenomena within the specified area, such as coastal zones (Burrough et al. 2015; Nakhli and Ghazi 2008). This study utilized a comprehensive approach, as presented in Fig. 2, utilizing satellite imagery and remote sensing techniques, to investigate the long-term transformations occurring at the lagoon's entrance and the downstream segment of the main channel. The study was assisted by the use of GIS mapping methods, which allowed for a detailed examination of these changes over time. Landsat optical images, as shown in Fig. 3 and detailed in Table 1, were carefully chosen for each decade, taking into account considerations such as image availability and cloud coverage, which is a factor that affects data availability in coastal zones (Green et al.1996). These satellite images, obtained from the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov/), were selected as the primary data source.

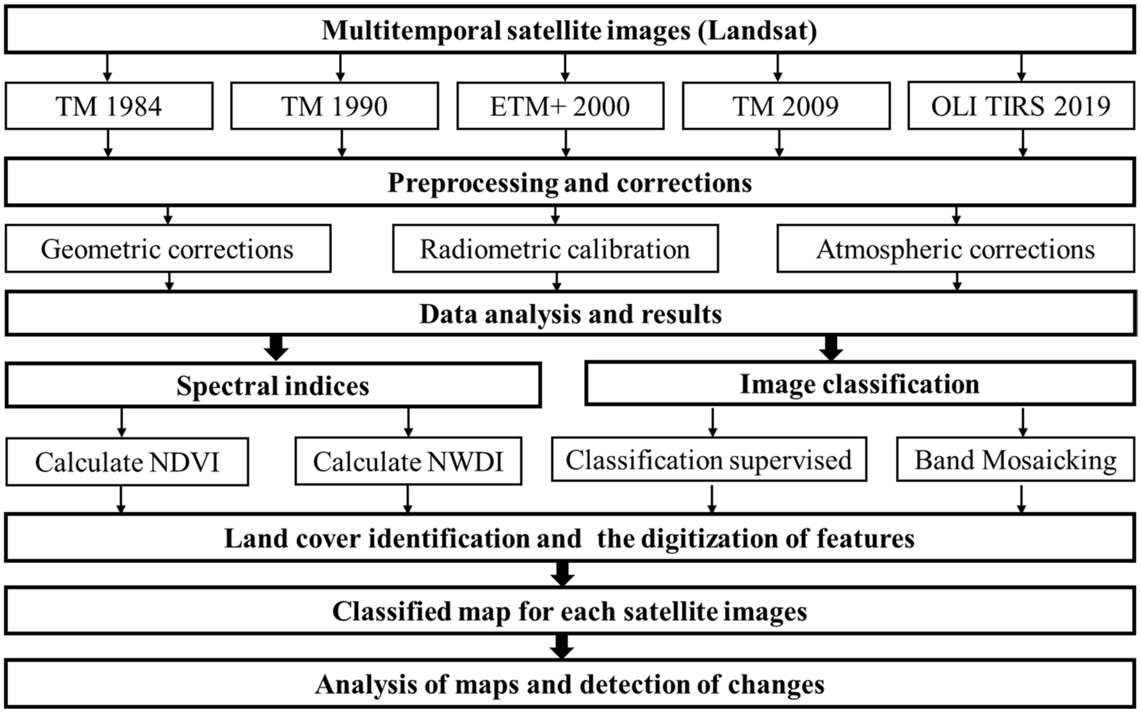

Fig. 2 Satellite image processing and analysis methodology

These satellite images were subjected to a series of meticulous corrections (Laignel et al. 2023; Toure et al. 2019). These include atmospheric corrections to mitigate atmospheric effects, radiometric calibration to normalize pixel values, and geometric corrections to rectify distortions caused by the sensor and the Earth's curvature. Furthermore, noise reduction techniques were employed to diminish any unwanted artifacts or irregularities present in the images. The satellite images utilized have a spatial resolution of 30 m. To conduct a thorough analysis of these satellite images and accurately differentiate between various features, we generated various false-color composites of each image, as shown in Table 1. These false-color composites serve as valuable tools for enhancing the visibility and contrast of distinct elements within the imagery (Liu et al. 2018). The GIS software ArcMap 10.3 was employed to code different bands in blue, green, and red, respectively. These band combinations were chosen methodically and with the ability to discern distinct spectral signatures of distinct elements within the study area, i.e., water bodies, vegetation cover, tidal flats, and sand dunes. Furthermore, we employed the Normalized Difference Vegetation Index (NDVI) (Laignel et al. 2023; Toure et al. 2019), as given in Eq. 1 (Rouse et al. 1974), to accurately measure the vegetation coverage and patterns. In addition, we employed the Normalized Water Difference Index (NWDI) (Laignel et al. 2023; Toure et al. 2019), as detailed in Eq. 2 (Gao 1996), to assess the extent of water bodies (Ahmed and Akter 2017; Gao 1996).

$$\text{NDWI} = \text{GREEN}-\text{NIR}/\text{GREEN} + \text{NIR} \tag{1}$$

$$\text{NDVI} = \text{NIR}-\text{RED}/\text{NIR} + \text{RED} \tag{2}$$

Figure 4 depicts the important role that NDVI and NDWI play in distinguishing various features within the study area. This visual example is based on an analysis of the Landsat image captured in 2019, showcasing how these indices contribute to a clearer differentiation of distinct elements within the landscape.

Last but not least, we used a supervised classification approach to improve the accuracy of our land cover identification process. Following that, armed with the wealth of information gathered, we set about digitizing and mapping each distinguishing feature. This comprehensive approach enabled us to examine and document the dynamic changes that occurred within the study area throughout our research, providing a thorough and detailed account of its evolution over time. It's important to highlight that these findings were later verified and validated through an on-site field visit conducted in February 2022 within the lagoon area.

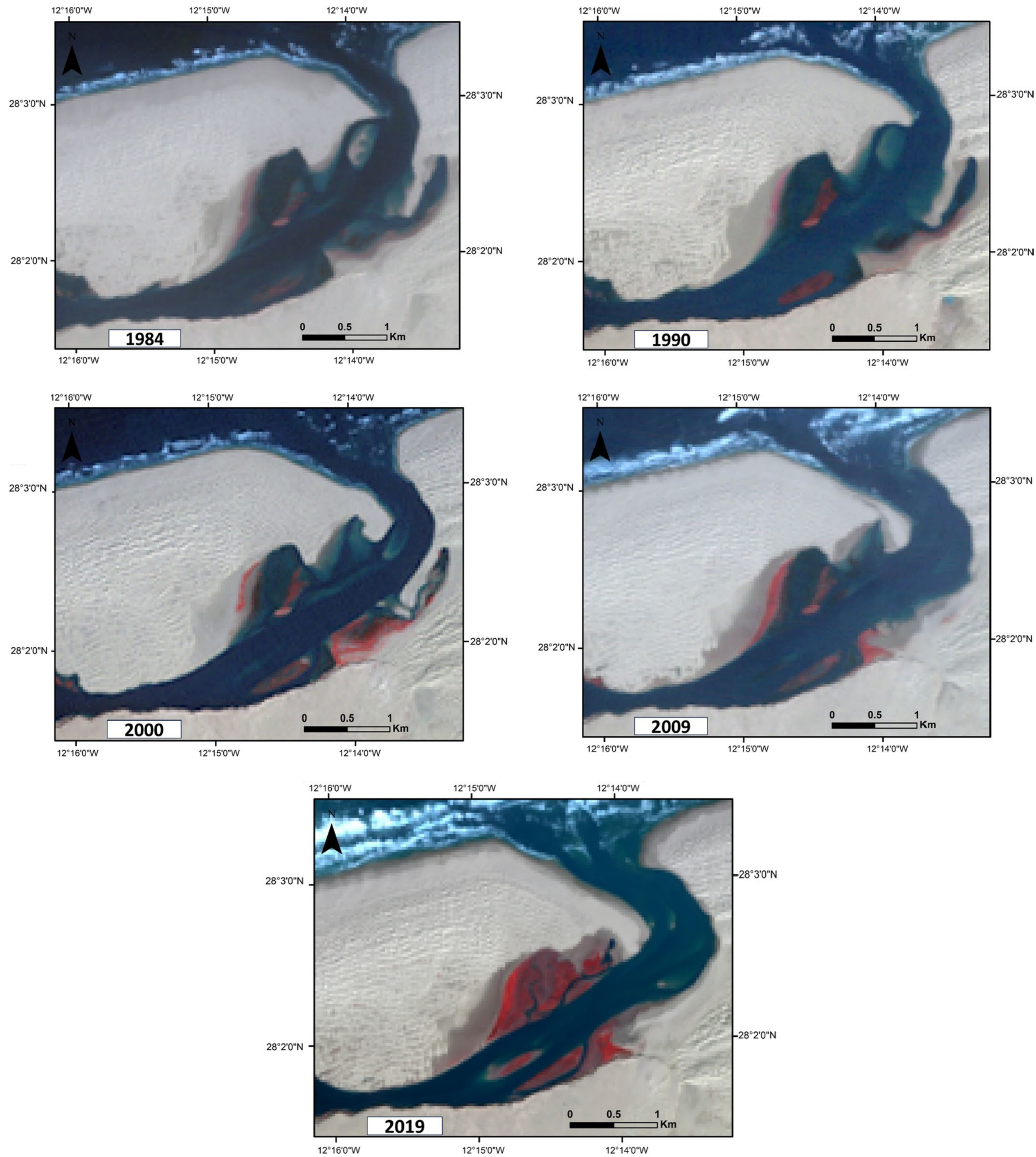

Fig. 3 Landsat standard false color composite of selected images for spatiotemporal evolution analysis of the Khenifiss Lagoon inlet and downstream zone of the main channel from 1984 to 2019. L5 TM Bands 4, 3, 2 RGB, L7 TM Bands 4, 3, 2 RGB, and L8 TM Bands 5, 4, 3 RGB. Vegetation is displayed in red, water in deep blue, sand dunes typically appear as shades of beige, and sandy tidal flats are often represented as brown

Table 1 Detailed information on selected satellite images for remote sensing analysis, band combinations used to create Landsat RGB color composite images, their conforming wavelengths, and applications

Date	Satellite	Sensor	Resolution in meters (m)	Band combination in RGB (Liu et al. 2018)	wavelengths	Application (Liu et al. 2018)
September 1984	Landsat 5	TM	30 m	4-3-2	NIR-Red-Green	Vegetation mapping;
December 1990	Landsat 5	TM		5-3-1	SWIR-Red-Bleu	Water bodies mapping;
February 2000	Landsat 7	ETM+		5-4-1	SWIR-NIR-Bleu	Topographic textures; Lithological Identification
November 2009	Landsat 5	TM				
December 2019	Landsat 8	OLI TIRS		5-4-3	NIR-Red-Green	
				6-4-2	SWIR-Red-Bleu	
				6-5-2	SWIR-NIR-Bleu	

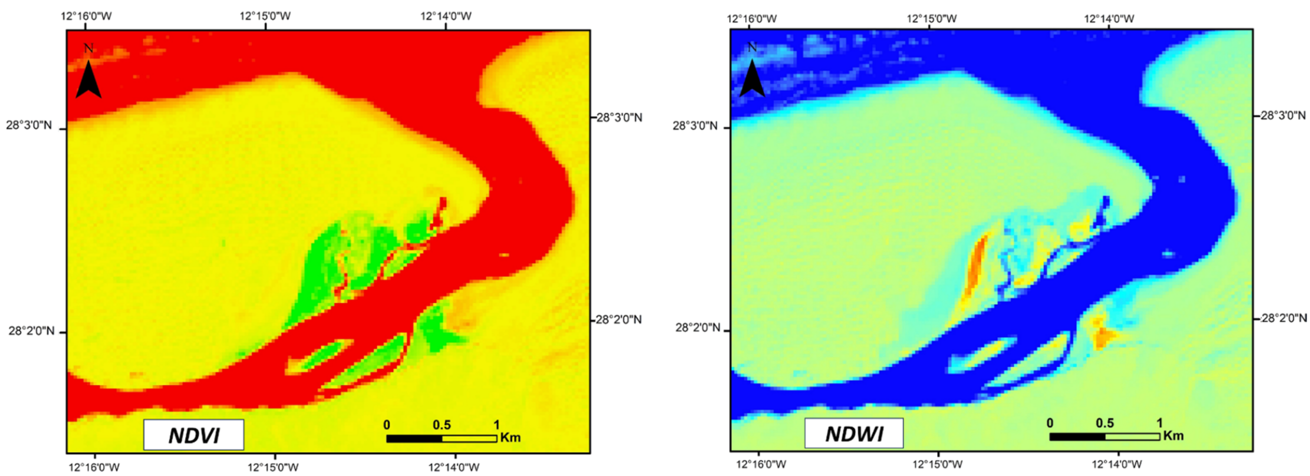

Fig. 4 Application of NDVI and NDWI Indices on the Landsat Image from 2019 in the Study Area. The extent of vegetation cover is determined using NDVI indices, with vegetation represented in green. NDWI, on the other hand, is utilized to evaluate the extent of water bodies, which are depicted in deep blue and tidal flats, indicated in light blue

Wind and wave data

Due to the unavailability of accessible records from wave buoys and meteorological stations in the Khenifiss area, we had to rely on alternative sources to acquire crucial wave and wind data. This decision was prompted by the significant absence of such data within the study region. To address this data gap, we primarily relied on a valuable resource, the Puertos del Estado, which is a reputable institution known for its comprehensive oceanographic data. The specific wave and wind data for each year of the study period can be accessed on https://www.puertos.es/en-us/oceanografia/Pages/portus.aspx. These data were collected from the nearest measurement point to the entrance of Khenifiss Lagoon, which had coordinates of 13.00° W and 28.25° N.

The selection of wind roses and wave roses is intentional, aligning with the intervals of satellite images employed in the study. This strategic decision facilitates the identification of changes in two pivotal factors – wind and waves – that exert a substantial influence on the lagoon's dynamics, in addition to tidal effects. By synchronizing the analysis with the intervals of satellite images, our study aims to offer a thorough understanding of how fluctuations in wind and wave patterns contribute to the lagoon's dynamics over time. Maintaining this consistency is vital for precisely correlating variations in these factors with the corresponding satellite data.

Results and discussion

The morphology or shape of the inlet, which connects a coastal water body such as a coastal lagoon with the open sea, is typically associated with the supply, transport, and deposition of sediments resulting from the interplay of various factors, including tidal movements, wave action, coastal currents, and river inflows. The analysis of processed satellite images of the Khenifiss Lagoon entrance and its corresponding downstream main channel from the years 1984, 1990, 2000, 2009, and 2019, in conjunction with the generated maps derived from these images, enables the identification of the morphological evolution of the downstream area of the Khenifiss Lagoon over the past four decades. The findings of this study reveal significant changes that are observable in the spatial and temporal distribution of the vegetation expansion within this part of the lagoon. These changes are also pronounced in three distinct sections of the lagoon's downstream zone: the inlet, the right bank, and the left bank, in terms of sediment deposition, eroded zones, and dune-induced sedimentation. Similarly, these changes are notable in terms of the number and size of islands present within the main channel at each of the dates. These changes had an impact on the position of the main channel throughout this period and, evidently, the hydrodynamics of the lagoon. During the study period, the transformation of the lagoon's downstream zone, including the entrance, has been dynamic, which has important implications for the hydrodynamics and connectivity of the lagoon with the surrounding coastal environment. These findings are in line with the research conducted by Nogueira et al. (2022) on the Foum Agouitir inlet, emphasizing the dynamic nature of this environment, which undergoes significant transformations over time. These fluctuations have a significant impact on the geochemical characteristics of the lagoon, sediment deposition patterns, and vegetation progression (Nogueira et al. 2022). The differential developments on the left and right banks of the lagoon showcase the intricate interplay between sediment deposition and erosion processes influenced by factors such as wind action, wave action, and sea level changes. The evolving landscape not only impacts the physical features of such a coastal ecosystem but also influences the ecological dynamics and habitat distribution within it (Pérez-Ruzafa et al. 2019). It is crucial to recognize these changes in the context of ongoing environmental shifts and to consider their potential effects on coastal management and preservation strategies.

Characteristics of wind and their effects on the lagoon entrance

Wind forcing plays a critical role in shaping the hydrodynamics and morphology of the Khenifiss Lagoon inlet (Nogueira et al. 2022). Furthermore, Rozas (1995) shows that winds along coastal regions can cause transient variations in water levels within estuaries. Wind stress exerted on ocean waters toward the coast typically leads to an increase in estuarine water levels as it pushes seawater into the estuary (Rozas 1995). Conversely, when winds propel coastal waters away from the shore, they have the opposite impact, causing a decrease in estuarine water levels (Rozas 1995). While this meteorological influence may not be as strong as the gravitational pull of astronomical tides in mesotidal and macrotidal environments along the Atlantic Coast, it is especially strong during neap tides (Boon 1975), which is the case of Khenifiss Lagoon. In addition, in coastal ecosystems such as the Khenifiss Lagoon, the presence of prevailing ocean-continent winds enhances the rate at which the lagoon fills, while emptying velocities experience an increase when winds blow from the continent toward the ocean (Morton 1994).

Wind patterns in Khenifiss Lagoon have the potential to significantly influence coastal sedimentation and sand drifting (Nogueira et al. 2022). These wind patterns have had a significant impact on the morphology and hydrodynamics of the lagoon over time (Nogueira et al. 2022). An examination of sea surface wind data for the lagoon's region, as shown in wind roses in Fig. 5, reveals a prevailing wind direction originating from the ocean and blowing inland, intersecting the coastal area at an oblique angle, primarily from the northeastern quadrant, with average speeds of 6 m/s and frequently exceeding 8 m/s. Elbelrhiti et al. (2005) also mention that this wind pattern is known as one of the most consistent trade winds in the world. Throughout the study period, notable changes have occurred in the inlet and the main tidal channel within the lagoon (Figs. 7 and 8). These changes are characterized by a significant expansion in their dimensions, resulting in a winding configuration and a marked shift towards a more sinuous shape of the main channel. These changes may influence water circulation and water residence time within the lagoon, since the geomorphology of a coastal lagoon, including the characteristics of its inlet, governs the hydrodynamics of the lagoon (Bird 1994).

Characteristics of waves and their effects on the lagoon entrance

Understanding wave directions near the shoreline is critical. Knowing the directions of wave propagation and their frequencies is extremely useful for understanding sediment movements observed in coastal areas, which eventually result in the formation of sandbars and beach erosion (Mahé 1957). Almost always, there is a noticeable swell on the entire western coast of Africa, generally unrelated to the local coastal weather conditions (Makaoui et al. 2005; Orbi and Nemmaoui 1992). This swell is primarily caused by both strong and consistent winds with minimal direction changes, slow-moving cold fronts, or, more commonly, barometric depressions passing far out in the ocean between the Azores and Iceland (Orbi and Nemmaoui 1992). The largest swells occur once or twice a year and can reach heights of 7–9 m (Orbi and Nemmaoui 1992). These robust swells are most frequent during the autumn and winter months. As they approach the coast and encounter shallow depths, they break along the shoreline, continuously agitating the waters of the coastal zone (Makaoui et al. 2005; Orbi and Nemmaoui 1992). The currents generated by this swell often lead to

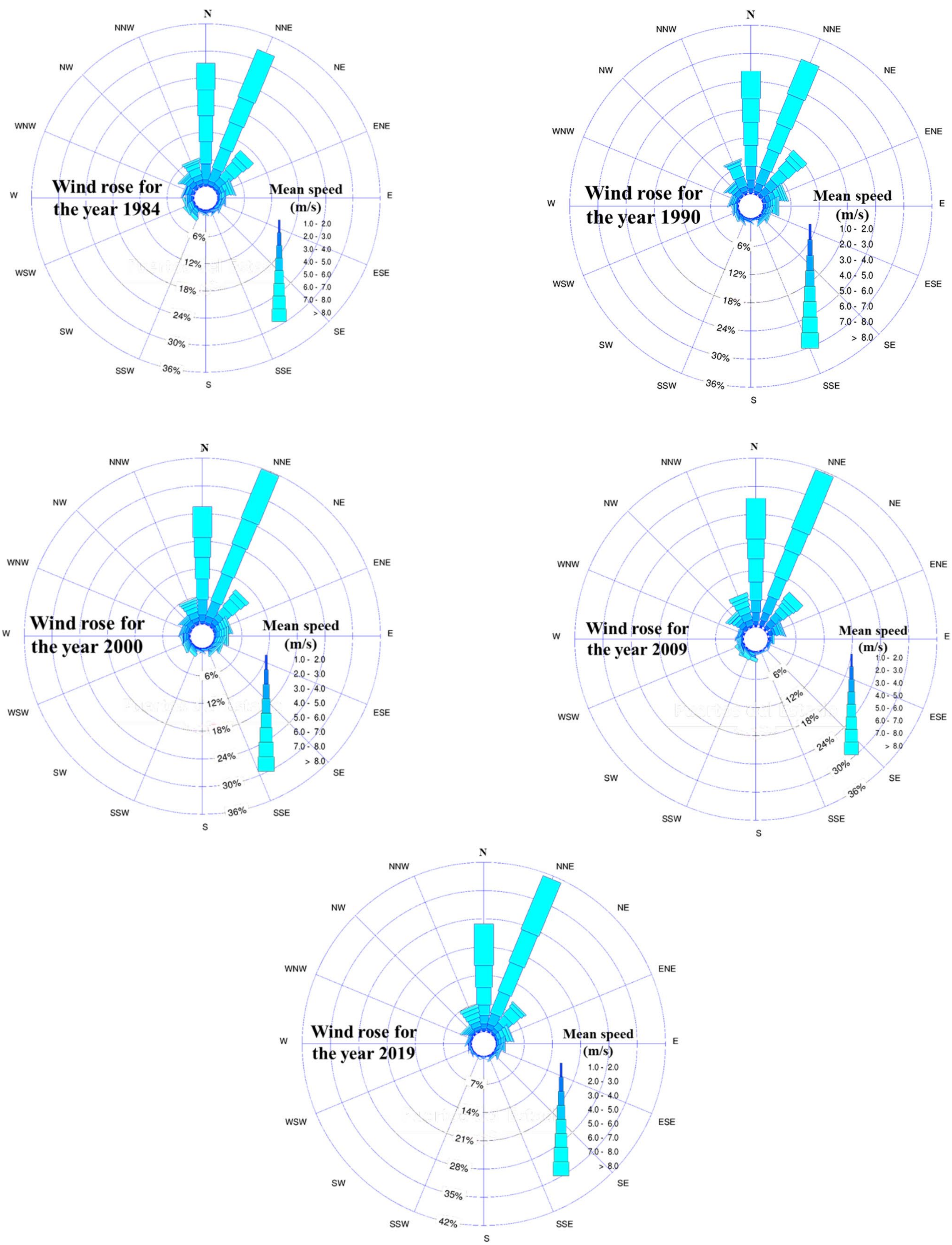

Fig. 5 Wind rose for the years 1984, 1990, 2000, 2009, and 2019 in the study area

the siltation of certain ports (Makaoui et al. 2005; Orbi and Nemmaoui 1992). The hydrodynamics of Khenifiss Lagoon are primarily influenced by a semidiurnal astronomical tide, which occurs with a frequency of two flooding events each day (Lakhdar Idrissi et al. 2000). However, similarly to the Atlantic Ocean coast, the entrance of the lagoon is subject to wave influence (Orbi and Nemmaoui 1992). An analysis of wave data impacting the lagoon's inlet, depicted in the wave roses in Fig. 6, demonstrates a consistent northward (N) prevailing direction of incoming waves. This dominant trend shows an increasing annual percentage from 73% in 1984 to over 80% in 1990, 2000, and 2009, and a peak of almost 90% in 2019. In contrast, the annual percentage of waves coming from the northwest (NW) does not exceed 14%, and the frequency of waves coming from other directions such as the northeast (NE), the west (W), and the east (E) remains minimal. The prevailing significant wave height falls within the range of 0–2 m for over 64% of the year, while wave heights ranging from 2 to 3 m occur less frequently, at a rate of fewer than 32%. Rarely does the significant wave height surpass 3 m, and occasionally, it can even exceed 5 m in the region. The action of the waves prevents the deposition of silt and clay in the entrance and main channel (Nichols and Boon 1994). Instead, fine sediments are transported by tidal currents and deposited in protected margins or marshes (Nichols and Boon 1994). The configuration of a lagoon entrance is the product of the dynamic interplay between sea waves, incoming tides (flood current), and outgoing tides (ebb current) (Bird 1994). Flood currents, typically driven by tidal inflows, transport sediment into the entrance, leading to its potential reduction and eventual closure (Bird 1994). Conversely, ebb currents, along with the discharge of floodwaters from the lagoon, work in opposition to this process by helping to maintain the entrance's openness (Bird 1994). In the case of the Khenifiss Lagoon, it is identified as a mesotidal environment, featuring a tidal range that fluctuates between approximately 1.5 and 3 m (Beaubrun 1976). The hydrodynamic characteristics of the lagoon include a current velocity that can peak at 110 cm/s during the spring tide (Lakhdar Idrissi et al. 2004). These hydrodynamic features hold particular significance in the context of preserving the openness of the lagoon entrance and ensuring its continuous connection with the ocean. The entrance is dominated by ebb currents (Lakhdar Idrissi et al. 2004). In such a case, the stronger ebb velocities effectively flush suspended sediment and can slow down or even prevent the sedimentary infilling process that typically occurs in most lagoons (Nieblas et al. 1999). Regarding of the Khenifiss Lagoon, we propose that the combined effect of waves and the specific dominance of ebb currents at the entrance play a critical role in maintaining the openness of its main inlet. This enables the continued exchange of water between the lagoon and the open sea, thereby maintaining the lagoon's ecological balance.

Spatiotemporal evolution of vegetation coverage in Khenifiss Lagoon entrance

Vegetation has a significant impact on the hydrodynamics of coastal wetlands, such as estuarine marshes (Rozas 1995). It can influence the marsh hydroperiod by changing the topography of the marsh surface, and it plays an important role in stabilizing the marsh substrate, promoting sediment accretion, and contributing organic matter to the sediment layers (Reed and Cahoon 1992; Rozas 1995). It also hinders water flow on the marsh surface, leading to delays in the initiation of flooding during a rising tide and the drainage of the marsh as the tide recedes (Borey et al. 1983). Khenifiss Lagoon exhibits modest floral diversity, totaling 25 species, reflecting a restricted range of habitats, predominantly consisting of an estuarine system devoid of freshwater input and a temporary marshy system (Hammada 2007). The vegetation within the lagoon can be categorized into two systems: estuarine and continental, with the estuarine system being predominant (Hammada 2007). In the main channel, the dominant flora includes *Zostera noolti*, *Spartina maritima*, *Arthrocnemum macrostachyum*, and various algae species (Hammada 2007). The extent of vegetated shore areas, as displayed in Table 2, exhibited fluctuations during the study period. Vegetation is primarily concentrated in the downstream region adjacent to the entrance of the lagoon's main channel. Approximately 55.11 hectares of vegetated shoreline were measured in the first year of observation, 1984. Then, by 1990, this area shrank to 50.27 hectares, but by 2009, it had expanded to reach 80.48 hectares. But then there was a decrease, and in 2009, the area was only 53.54 hectares. Yet, there was a subsequent resurgence in development, resulting in an expansion to 103.9 hectares by 2019.

In the context of the Khenifiss Lagoon, fluctuations in the tidal limit over time exert a significant influence on the distribution of vegetation zones (Nogueira et al. 2022). The expansion of vegetation within the lagoon's entrance and main channel from 53.54 ha in 2009 to 103.9 ha in 2019 has led to a reduction in the overall water body. This is particularly notable, because, as vegetation density increases, a greater amount of sediment is retained (Nogueira et al. 2022). Likewise, as plants like *Zostera noolti*, *Spartina maritima*, and *Arthrocnemum macrostachyum* proliferate, they gradually encroach upon the open water space, altering the lagoon's landscape and ecological dynamics. The ecosystem may be significantly impacted by this transformation, which may have an impact on local biodiversity, habitat availability, and water flow. It emphasizes how crucial it is to keep an eye on and control vegetation growth in the lagoon to preserve its ecological functions and balance.

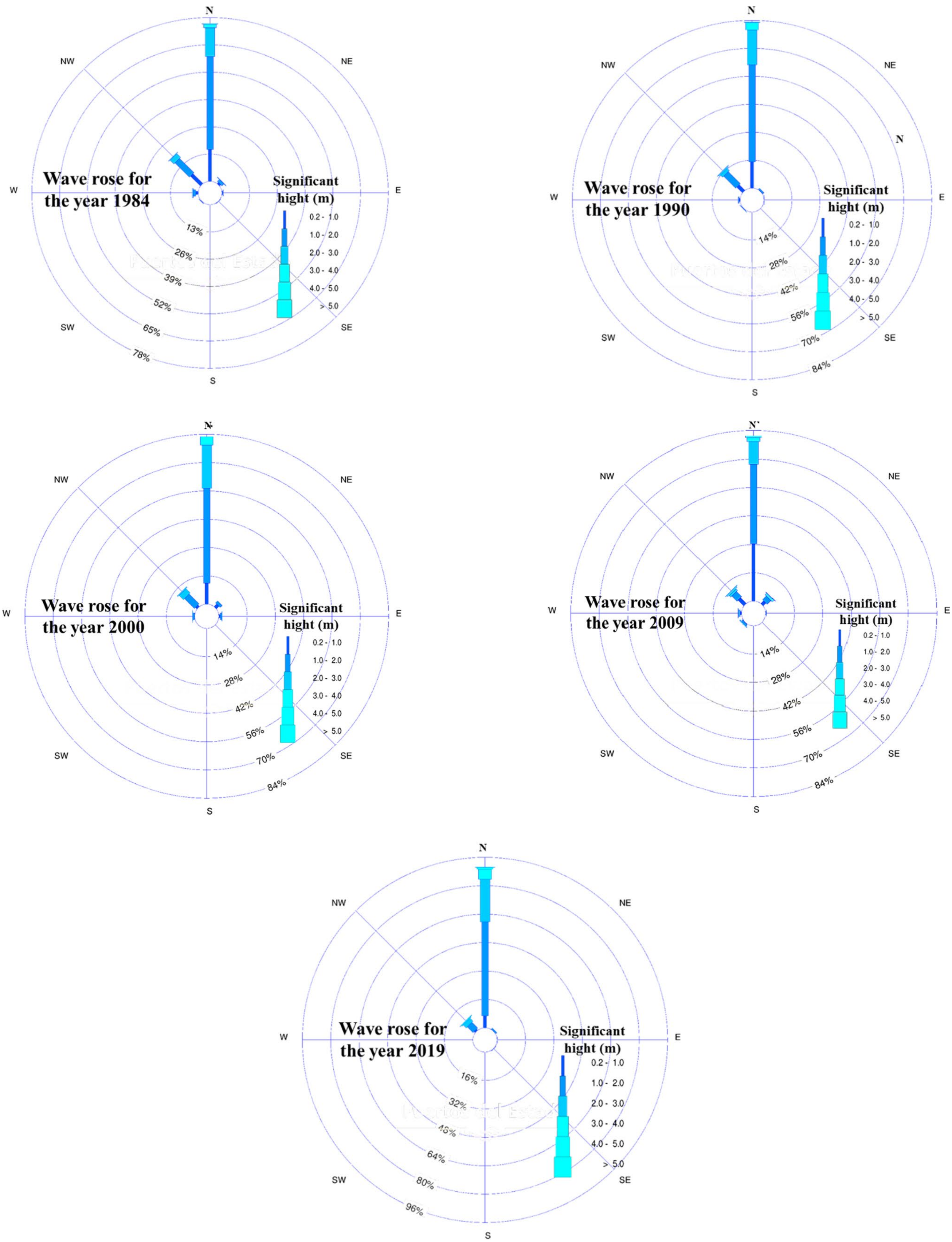

Fig. 6 Wave rose for the years 1984, 1990, 2000, 2009, and 2019 at the Khenifiss Lagoon inlet

Table 2 Changes in vegetation coverage at the entrance zone of the Khenifiss Lagoon from 1984 to 2019

Year	1984	1990	2000	2009	2019
Evolution of Vegetated shores space in hectares (ha)	55.11	50.27	80.48	53.54	103.9

Spatiotemporal evolution of sediment-related processes in Khenifiss Lagoon entrance

Figure 7 illustrates the spatial extent of the main features within the entrance of Khenifiss Lagoon and its adjoining areas at five time points: 1984, 1990, 2000, 2009, and 2019. The analysis of the spatiotemporal evolution of sediment-related processes at the entrance of Khenifiss Lagoon reveals a dynamic landscape of sedimentation patterns between 1984 and 2019. Figure 8 illustrates and quantifies the spatial distribution of these transformations. In this context, the sedimentary dynamics manifest across three discernible categories, as outlined in Table 3, which are as follows:

- *Sediment deposition in tidal flats:* The tidal flats, including vegetated shores, have witnessed significant sediment deposition spanning an area of approximately 148.93 hectares along the study period. These areas play an essential role in shaping the lagoon's overall sedimentary makeup by acting as important reservoirs for accumulating sediments.
- *Dune-induced sedimentation:* Fig. 9 depicts the effect of sand dunes in determining the sedimentation dynamics of the Khenifiss Lagoon. The Hassi Fleiga sand dunes, in particular, support sediment deposition over a large area, covering around 57.39 hectares. This influence is most noticeable in the inlet's eastern part and extends to both the left and right banks of the main channel, as illustrated in Fig. 8. Dune-induced sedimentation is an example of how geomorphological characteristics can shape the distribution of sediment in the lagoon. A sand river, oriented NNE-SSW, is solely responsible for the main siltation occurring in the Khenifiss Lagoon (Saltani et al. 2015). This dune structure is fed by sediment inputs originating from the eastern part of the Khenifiss Lagoon (Saltani et al. 2015).
- *Eroded areas:* In contrast to deposition, certain sections at the entrance and the downstream part of the lagoon’s main channel have experienced erosion, resulting in an area measuring about 99.14 hectares in size. The extent of eroded areas emphasizes the imbalance between sediment influx and removal, underscoring the asymmetry in these sedimentary processes.

In estuaries, the tidal amplitude is influenced by the dimensions of the inlet (Hackney and Yelverton 1990). Increased inlet dimensions in estuaries increase tidal amplitude at the upper estuary, because the larger inlet allows a greater volume of water to enter during flood tides (Hackney and Yelverton 1990). The entrance of Khenifiss Lagoon (Foum Agouitir) gradually enlarged over the study period between 1984 and 2019, with a progressive size increase in this period from 1450 m in 1984 to 1650 m in 2019. The eastern part of the entrance (on the left bank) has experienced significant development of the sand barrier due to the advancing sand dunes that characterize the region. This sand barrier had extended progressively by about 100 m by 2019 inside the inlet, compared to its state in 1984. On the contrary, the western part of the sand barrier (on the right bank) has experienced a more significant retreat, with some areas witnessing a progressive decline over the study period to an extent between 200 and 300 m due to erosion. Noteworthy changes in the number and size of islands within the main channel can be seen at each of the recorded dates, with a noticeable increase in both factors over the study period.

Significant changes have occurred within the lagoon's downstream zone during the period of study, resulting in the main channel becoming narrower and adopting a more meandering shape. In addition, these changes have led to an expansion of the vegetated shores on the left and right banks. These observed changes highlight the dynamic nature of coastal ecosystems as well as the intricate relationships between geological processes and ecological dynamics. Figure 8 and Table 3 provide, respectively, a visual representation and quantification of sediment deposition (encompassing dune-induced sedimentation) and erosion within the downstream zone and the entrance of the Khenifiss Lagoon. The results highlight a significant spatial imbalance between these two processes, shedding light on the issue of lagoon silting. Approximately 206 hectares are impacted by sediment deposition, compared to only 99.14 hectares by erosion. This difference emphasizes the lagoon's predominant dominance of sedimentation over erosion. The results highlight the worry that sedimentation is overtaking erosion as the dominant geological process, ultimately resulting in the lagoon's progressive silting.

Figure 10 depicts the temporal changes in the main features of Khenifiss Lagoon. It depicts the progressive expansion of sand dunes, which gained an extent of 1.55 km^2 over the extent of other features in the studied area. This expansion contrasts with a reduction in the water body extent during the study period, decreasing from 4.8 to 3.8 km^2, accompanied by a slight retreat in the desert plateau caused

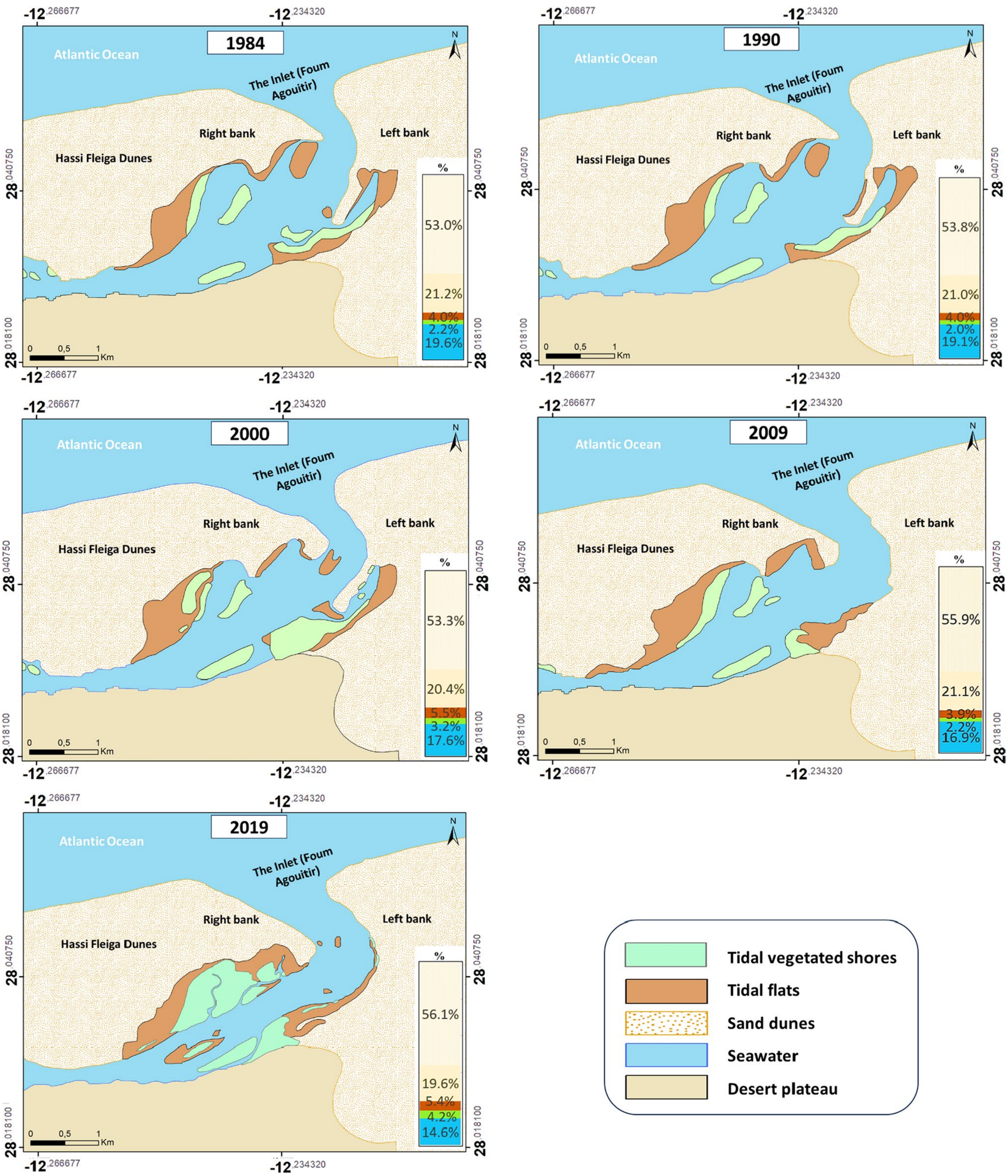

Fig. 7 Cartographic representation of key features at Khenifiss Lagoon's entrance and adjacent zones across five time points: 1984, 1990, 2000, 2009, and 2019, using satellite imagery. The diagrams present the proportional representation of various entities on each map, with the percentage of water exclusively reflecting the water body within the main channel

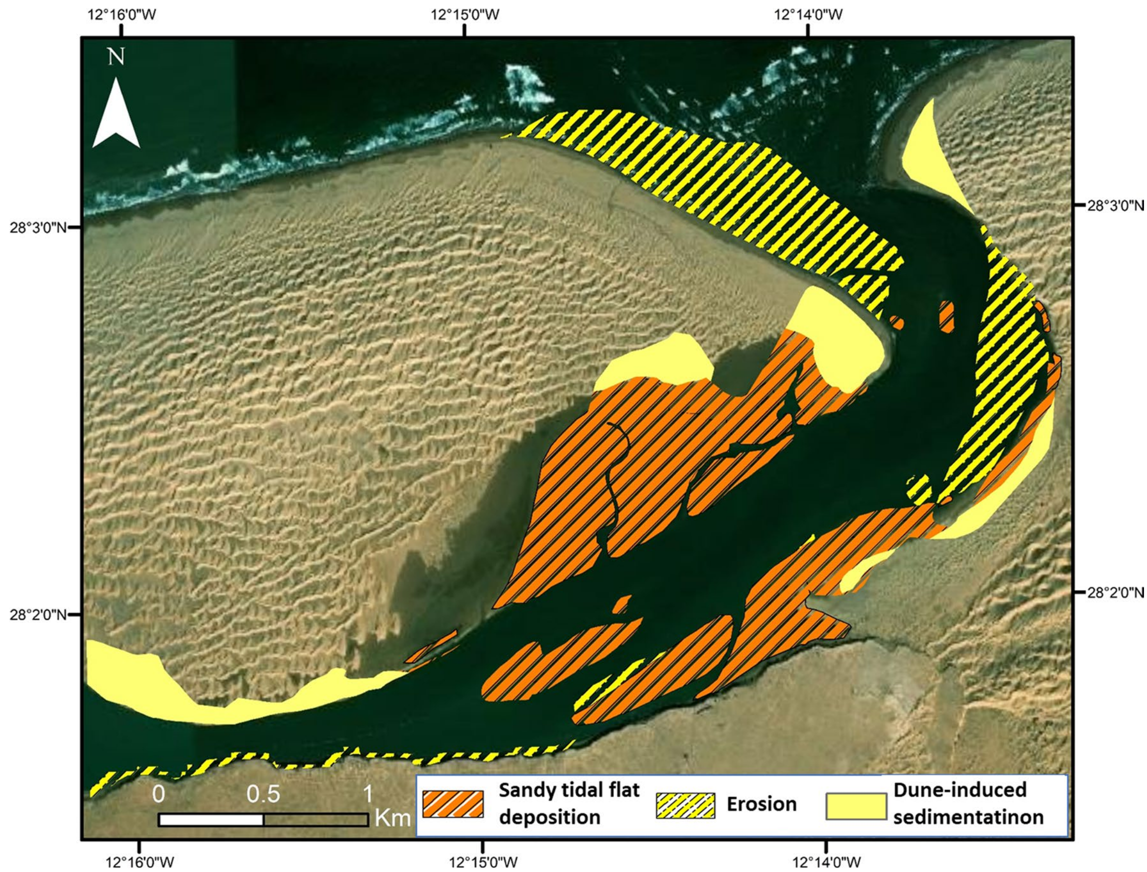

Fig. 8 Spatial distribution of sediment-related processes within the entrance and downstream main channel of Khenifiss Lagoon during the period extending from 1984 to 2019

Table 3 Changes in areas impacted by erosion, deposition, and dune advancement at the Khenifiss Lagoon entrance zone between 1984 and 2019

Processus	Sediment deposition in tidal flats (including vegetated shores)	Eroded areas	Dune-induced sedimentation
Total surface area in hectares (ha)	148.93	99.14	57.39

by erosion. Fluctuations are evident in the tidal flat and vegetation, with a notable increase over the past decade contributing to the narrowing of the lagoon's main channel.

In Fig. 11, a simplified conceptual model illustrates the progressive narrowing of Khenifiss Lagoon, outlining three distinct scenarios. The first scenario depicts the advancement of sand dunes over the water body, resulting in the constriction of the main channel and the formation of intertidal flats adorned with sea grass vegetation. This process promotes sediment deposition and facilitates the accretion of both intertidal and supratidal flats. The second scenario illustrates the consequences of sand dune progression, leading to silting and the subsequent narrowing of the main channel. In the third scenario, the subtidal area undergoes vegetative colonization by sea grass, fostering sediment deposition and contributing to the accretion of intertidal and supratidal flats. These scenarios collectively capture the dynamic processes shaping the evolving morphology of Khenifiss Lagoon.

The Khenifiss Lagoon exhibits a distinct feature of limited accommodation space, a characteristic that contributes to the reduction of available main channel space. This limitation affects various crucial zones, encompassing the subtidal zone, intertidal flat, and upper marshes. The consequence of this phenomenon is a discernible net loss of wetlands within the lagoon, consistent with the findings of Nogueira et al. (2022). The depletion of these essential habitats underscores the ecological challenges faced by the lagoon, emphasizing the need for thoughtful conservation and management strategies.

The enlargement of the inlet may appear to improve water circulation at first by increasing the exchange between the lagoon and the sea. Several observed changes,

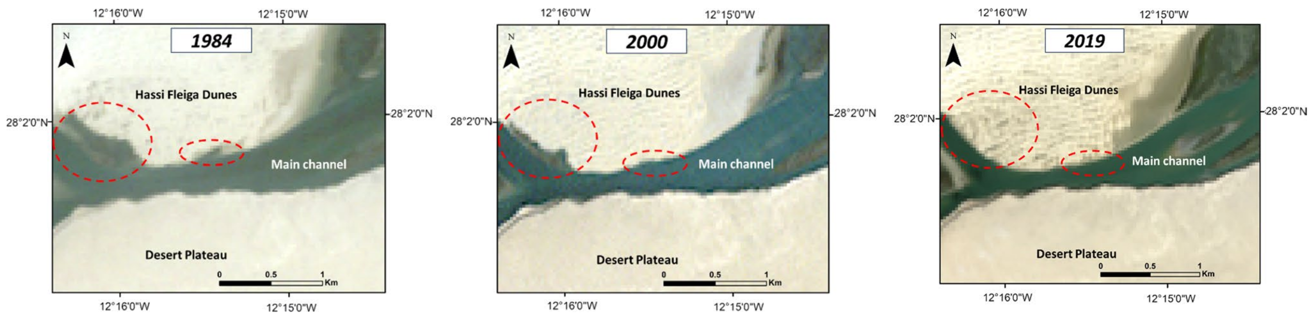

Fig. 9 True-color Landsat imagery illustrates the impact of sand dunes on the silting of the lagoon's main channel, leading to its gradual narrowing. Red circles indicate the advancement of sand dunes encroaching upon the waterbody at two specific locations within the main channel, observed at three distinct time points in 1984, 2000, and 2019

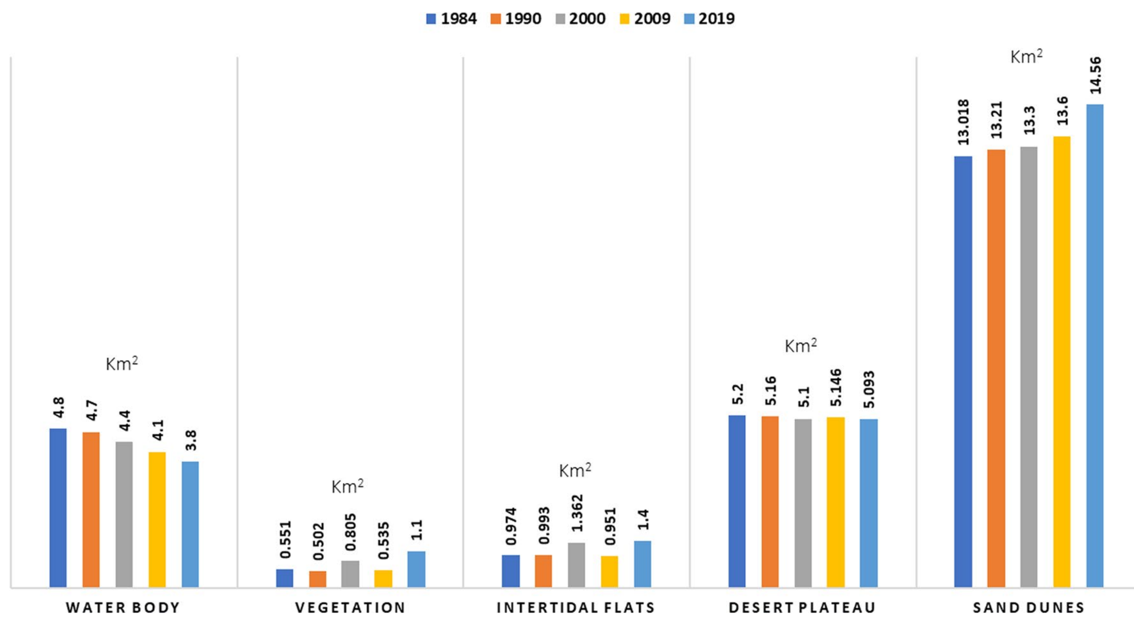

Fig. 10 Temporal variability in the size (Km^2) of the main features within Khenifiss Lagoon

however, raise concerns. The main channel has narrowed, vegetated shores have expanded, and sediment deposition has increased, leading to the expansion of tidal flats across water bodies and the formation of new islands within the main channel. These factors suggest that the inlet enlargement has influenced the balance between sedimentation and erosion processes, resulting in increased sediment deposition over erosion. This problem is exacerbated by the sediment introduced into the main channel by moving sand dunes. These observations strongly suggest that the main channel, which is critical to the lagoon ecosystem as a whole, is gradually closing. This is supported by the documentation from the Ministry of Equipment and Transport (2010), which reports reductions in depth within both the inlet and the main channel. Furthermore, residents of Khenifiss Lagoon and its surroundings have expressed concerns about the observed decline in the depth of the lagoon over recent decades (Amimi et al. 2021), which has made it difficult for fishing boats to navigate certain areas of the lagoon and has likely contributed to the decrease in fish stocks within the lagoon. This research assesses spatiotemporal changes at the lagoon entrance and its corresponding downstream main channel as observed through satellite imagery. Nonetheless, it is critical to recognize the limitations of this approach, as a thorough investigation into lagoon evolution necessitates a more in-depth examination. A thorough assessment of depth evolution within the lagoon at periodic intervals, in particular, is critical for gaining a comprehensive understanding of its evolution, particularly in determining whether or not it is undergoing closure. Nonetheless, this study should serve as a wake-up call. It emphasizes the critical need

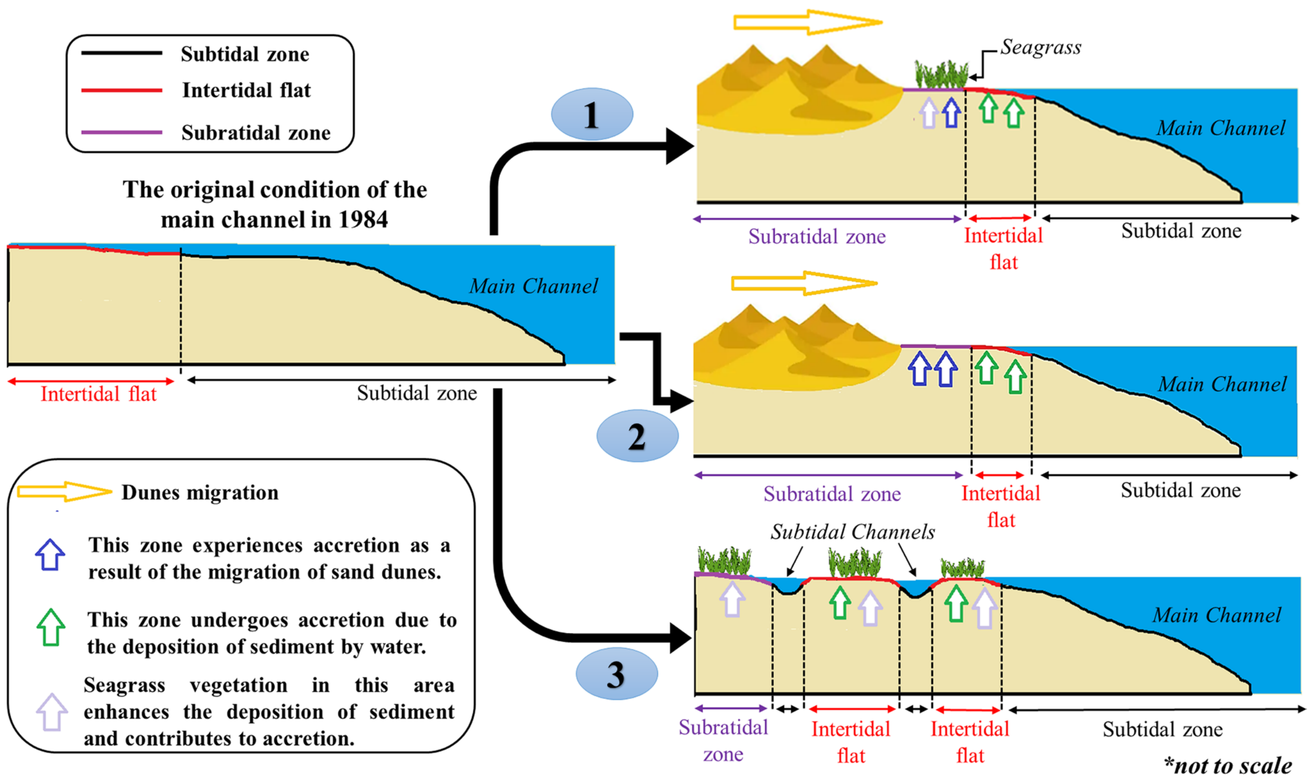

Fig. 11 Simplified conceptual model illustrating the narrowing of the Khenifiss Lagoon. Three scenarios are depicted: **1** Dune progression over the water body leads to the narrowing of the main channel and the formation of intertidal flats with seagrass vegetation, promoting sediment deposition and facilitating the accretion of both intertidal and supratidal flats. **2** Dune advancement over the water body results in silting and the narrowing of the main channel. **3** The subtidal area is being vegetated by sea grass, promoting sediment deposition and the accretion of intertidal and supratidal flats

for coordinated action to address the lagoon's changing dynamics and put into action strategies that aim to maintain the ecological balance and secure the lagoon's integrity for both current and future generations.

Sustainable management strategies for the Khenifiss Lagoon

Many coastal lagoons around the world are grappling with environmental issues that result in their narrowing. However, the distinctive feature of the Khenifiss Lagoon is its existence in an arid environment. Management strategies for coastal lagoons vary depending on numerous factors, including: geographical location, ecological characteristics, human activities in the surrounding areas, and the specific challenges or threats faced by each lagoon (De Jonge et al. 2012; Elliott et al. 2017; Puente-Rodríguez et al. 2015).

In the Chilika Lagoon, the largest brackish water coastal lagoon in Asia located in India, approximately 62% of the coastline has experienced varying degrees of accretion over the past four decades (1975–2015), while 25% remains stable and 13% faces low to high erosion, as reported by Baral et al. (2018). The lagoon has encountered a combination of increased siltation and choking due to the degradation of the drainage basin and the partial closure of the mouth connecting the lagoon to the sea (Samal 2011). In 2000, a significant intervention was undertaken to create an artificial inlet (Mahanty et al. 2016). After the establishment of this new inlet, there was a notable improvement in the ecological conditions of the lagoon, leading to enhanced productivity (Mahanty et al. 2016).

The Biguglia lagoon, located in the northern part of Corsica Island (France), is a shallow brackish coastal lagoon confined by a long sandbar that separates it from the sea. Seawater exchanges are regulated through a single narrow, shallow natural channel to the north (Erostate et al. 2022). The lagoon faces challenges with limited marine water inputs as the sea channel tends to naturally close due to sand accumulation, necessitating periodic human intervention for reopening. Regular activities, such as the artificial opening of the current channel and the cleaning of drainage channels, constitute active restoration measures (Erostate et al. 2022). These efforts show promising effects on the lagoon ecosystem in the medium term, illustrating the resilience of the lagoon to the effectiveness of human-induced changes.

In the San Jose Lagoon, located in an arid zone in Mexico, a significant reduction in its overall size has occurred.

Between 2001 and 2017, there was a 26% decline, primarily attributed to inadequate land planning, environmental fragmentation, and ineffective management strategies (Imaz-Lamadrid et al. 2019). This shrinkage, coupled with increasing evapotranspiration and rising sea levels, is likely to promote mineralization, resulting in a decline in the quality of surface water (Imaz-Lamadrid et al. 2019). As a result, adverse effects on vegetation cover are anticipated, and without appropriate management and effective measures to tackle these challenges, there exists a risk that the lagoon might ultimately vanish (Imaz-Lamadrid et al. 2019).

In Morocco, coastal lagoons confront various environmental challenges, with noteworthy issues such as silting and pollution (Mejjad et al. 2020). In contrast, the Khenifiss Lagoon stands out as the most pristine among Moroccan lagoons, showing no significant concerns regarding pollution levels (Mejjad et al. 2020; Tnoumi et al. 2021, 2022). However, this study and others (Amimi et al. 2021) emphasize legitimate concerns related to substantial silting in the inlet and the main channel, alongside wetland loss (Nogueira et al. 2022). These issues hold critical importance for the ecosystem's vitality, biodiversity, and socio-economic significance.

In the case of the Oualidia Lagoon in north Morocco, and light of various environmental challenges, particularly the reduction of depths and the upstream water confinement, a recommendation was made in 2006 to construct a sediment trap (Bouchkara et al. 2021, 2022). This trap was subsequently created in 2011 to capture the finest sediment in the upper part of the lagoon (Bouchkara et al. 2021, 2022). Consequently, the construction of the sediment trap enhanced the hydrodynamics of the lagoon, especially in the sandpit area, leading to a morphological transformation. This hydrodynamic shift changed the lagoon from a constrained basin to a more restricted state following the dredging of the sediment trap (Bouchkara et al. 2021, 2022). On the Moroccan Mediterranean coastline, particularly within the Nador lagoon, the establishment of a new, broader, and deeper inlet has proven to enhance hydrodynamics. This improvement not only contributes to the overall health of the ecosystem but also triggers a shift towards ebb dominance, thereby influencing the mid-term morphological evolution (Maicu et al. 2021). This improvement also has a positive impact on the sedimentary status and sediment redistribution of the lagoon seabed, enhancing its quality (Kousksou et al. 2015).

All these cases exemplify the favorable outcomes achieved through the implementation of effective management strategies for bolstering the conditions of coastal ecosystems. They also underscore the effects of neglecting the ongoing alterations faced by lagoons, which can lead to significant issues for the entire ecosystem. Ignoring the narrowing problems of the lagoon poses a direct threat not only to the ecosystem's health but also to the vital services it offers to the local community. Recognizing and addressing these challenges through effective management is crucial for the long-term sustainability of these coastal environments.

In the context of Khenifiss Lagoon, a primary concern revolves around a large shipwreck obstructing the inlet mouth that connects the lagoon to the sea (Ministry of Equipment and Transport 2010). This obstruction significantly disrupts the hydrodynamic circulation of seawater, leading to the formation of new islands that exacerbate the narrowing issue of the main channel (Amimi et al. 2021). In addition, the rapid growth of vegetation in subtidal and intertidal flats promotes sediment deposition, further contributing to the narrowing of the main channel. The migration of dunes within the main channel also plays a role in the substantial silting of the lagoon.

Figure 12 provides a visual representation of the diverse sediment-related processes along the shoreline of the Khenifiss Lagoon, expanding on the trends outlined in Figs. 7 and 8. In addition, it offers information on the total length of each process along the shoreline. Approximately, 27% of the shoreline in the study area remains stable, whereas 21.7% is currently experiencing erosion. Moreover, 23.6% and 27.8% are undergoing accretion due to sediment deposition and the progression of sand dunes, respectively. Understanding trends and fluctuations in shoreline positioning is valuable for policymaking in developing coastal zone monitoring and human interventions (Laignel et al. 2023). This map acts as a valuable tool for decision-makers, enabling them to develop informed strategies for the sustainable development, preservation, and restoration of the lagoon. In addition, it assists in pinpointing priority areas for intervention, empowering decision-makers to implement targeted measures that address the identified narrowing issues in the Khenifiss Lagoon.

The sustainable future of coastal zones hinges on our ability to enhance comprehension, governance, and anticipation of the developments in these environments (Laignel et al. 2023).To safeguard Khenifiss Lagoon, several management strategies can be considered to address the identified challenges. Start by giving priority to removing the obstructing shipwreck and reinstating normal hydrodynamic circulation. Ensure regular dredging and maintenance of the inlet mouth to prevent sediment buildup and sustain a vital connection between the lagoon and the sea. In addition, consider engaging in restoration projects to revive natural flow dynamics, fostering a sustainable balance between the lagoon and its encompassing environment. Implement dune stabilization techniques to curb dune migration within the main channel, thereby lessening sedimentation and mitigating adverse effects on the lagoon. Besides, it is imperative to formulate and execute an integrated coastal zone management (ICZM) plan encompassing the entire coastal ecosystem, with a specific focus on the lagoon, to foster a comprehensive approach

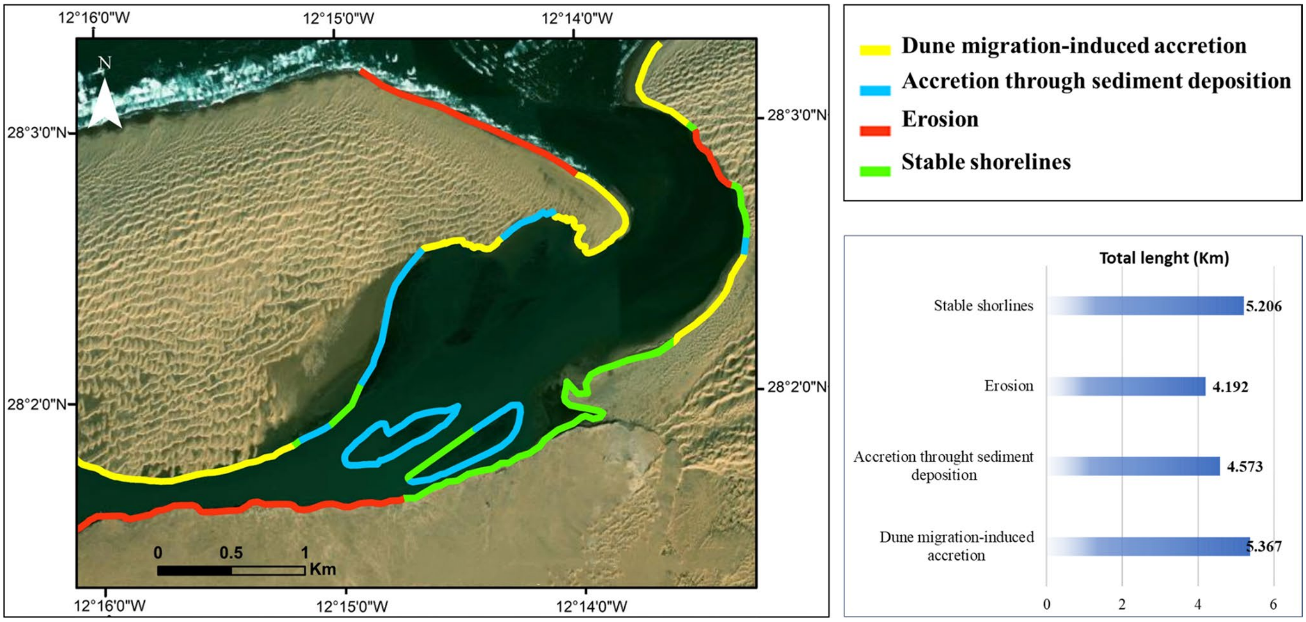

Fig. 12 Map shows the extent of each sediment-related process along the shorelines of the Khenifiss Lagoon. The diagram depicts the total length (Km) of each process along the shoreline

to conservation and sustainable utilization. Engage local communities, government agencies, and environmental organizations actively in both the planning and execution phases of ICZM. However, management strategies should be implemented alongside a monitoring program to track potential changes occurring in the entire ecosystem. Human interventions can induce alterations, and these changes, if not carefully observed and addressed, pose the risk of destabilizing the overall functioning of the ecosystem (Davies-Vollum et al. 2019). Therefore, a comprehensive monitoring framework is essential to assess the impact of management strategies and to proactively manage any unintended consequences that may arise, ensuring the sustained health and balance of the ecosystem.

Conclusion

This study used satellite imagery, remote sensing, and GIS mapping, along with historical wind and wave data, to comprehensively explore the long-term alterations occurring at the lagoon entrance and downstream main channel. Through the selection of satellite images, thorough corrections, and detailed analysis techniques, the research has provided insights into the changing sedimentation-related processes and vegetation cover of the lagoon over the past forty years. Over this period, several transformations have occurred that have influenced the shape and environment of the inlet and the downstream part of the main channel. These transformations have led to the inlet getting larger and the main channel becoming narrower, while the surrounding shores have become more vegetated and expanded. This has also caused an increase in sediment deposition, resulting in the expansion of sandy tidal flats and the creation of islands within the main channel. These changes indicate that the enlargement of the inlet has affected the balance between sedimentation and erosion processes, leading to a greater amount of sediment being deposited than eroded. The issue is exacerbated by sediment carried into the main channel by shifting sand dunes. Based on these observations, it strongly suggests that the main channel, which plays a role in the lagoon ecosystem, is gradually becoming closed off.

These findings are extremely alarming and necessitate immediate action to preserve the delicate equilibrium of the lagoon ecosystem and the vital services it provides to both the local community and the environment. These results strongly support the need to start a long-term monitoring program to evaluate the principal channel of the lagoon's changing condition. Consistent observations of water depth, sediment deposition, water quality, and vegetation extent should all be included in this program, giving scientists and policymakers crucial information with which to make decisions.

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Author contributions H. El Behja authored the initial draft of the manuscript text and created the figures. Material preparation, data collection, and analysis were conducted by H. El Behja, A. El M'rini, and D. Nachite. The primary manuscript text underwent editing and review by M. Abioui. All authors participated in the conception and design of the study. Subsequently, all authors collectively reviewed and engaged in discussions to enhance the manuscript.

Data availability The data that support the findings of this study are available from the corresponding authors, Hamza El Behja & Mohamed Abioui, upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abioui M, M'Barki L, Benssaou M, Ezaidi A (2018) Khnifiss lagoon-estuarine complex (Morocco): a coastal, marine, dune and Saharan ecosystem. In: ESW 3rd International Research Conference on Ecotourism & Environment, 29–31 July 2018, India, pp 28–29 (Abstract book)

Abioui M, Ferry S, Grosheny D, Içame N, Robert E, Benssaou M (2019) The Cretaceous marine onlap on the Paleozoic of the Anti-Atlas (Smara-Lâayoune Basin, South Morocco). Comparison with neighbouring regions. CR Geosci 351(7):498–507

Adnani M, Azzaoui MA, Elbelrhiti H, Ahmamou M, Masmoudi L (2018) Investigation of reddening patterns of dune sands—The megabarchans of Al-ghord Lahmar (Khnifiss National Park, South-West of Morocco). CATENA 162:230–244

Ahmed KR, Akter S (2017) Analysis of landcover change in southwest Bengal delta due to floods by NDVI, NDWI and K-means cluster with Landsat multi-spectral surface reflectance satellite data. Remote Sens Appl Soc Environ 8:168–181

Ahmed MH, El Leithy BM, Thompson JR, Flower RJ, Ramdani M, Ayache F, Hassan SM (2009) Application of remote sensing to site characterisation and environmental change analysis of North African coastal lagoons. Hydrobiologia 622:147–171

Amimi T, Elbelrhiti K, Adnani M, Elbelrhiti H, Chao J, Oubbih J (2021) Soil map of Khnifiss lagoon and its surrounding environment. Arab J Geosci 14(6):515

André A, Bons J, Bryssine G, Bryssine I, Delannoy H, Girot B (1975) Contribution à l'étude scientifique de la province de Tarfaya. Travaux de l'Institut Scientifique, Rabat

Baral R, Pradhan S, Samal RN, Mishra SK (2018) Shoreline change analysis at Chilika Lagoon Coast, India using digital shoreline analysis system. J Indian Soc Remote Sens 46(10):1637–1644

Barnes RSK (1980) Coastal lagoons. Cambridge University Press, Cambridge

Beaubrun PC (1976) La lagune de Khnifiss: premières observations sur les sédiments et l'hydrologie du milieu. Bull Inst Sci 1:50–65

Bird ECF (1994) Physical setting and geomorphology of coastal lagoons. In: Kjerfve B (ed) Coastal lagoon processes. Elsevier, Amsterdam, pp 9–39

Boon JD (1975) Tidal discharge asymmetry in a salt marsh drainage system. Limnol Oceanogr 20(1):71–80

Borey RB, Harcombe PA, Fisher FM (1983) Water and organic carbon fluxes from an irregularly flooded brackish marsh on the upper Texas coast, USA. Estuar Coast Shelf Sci 16(4):379–402

Bouchkara M, Mejjad N, El Khalidi K, Canu DM, Zourarah B (2021) An integrated environmental assessment of a coastal lagoon: the case of the Oualidia lagoon (Morocco). E3S Web Conf 298:02003

Bouchkara M, El Khalidi K, Benazzouz A, Erraji Chahid N, Joudar I, Zourarah B, Maanan M (2022) Study of morphodynamic and sedimentological changes in the Oualidia Lagoon (Morocco) using bathymetric data: first investigations after the sediment trap dredging. ISPRS Archives 46:53–63

Burrough PA, McDonnell RA, Lloyd CD (2015) Principles of geographical information systems. Oxford University Press, Oxford

Carruesco C (1998) Genèse et évolution de trois lagunes du littoral atlantique depuis l'Holocène: Oualidia, Moulay Bou Salham (Maroc) et Arcachon (France). Dissertation, University of Bordeaux 1

Dakki M, De Ligny W (1988) The Khnifiss lagoon and its surrounding environment (Province of L'ayoune, Morocco). Travaux de l'Institut Scientifique, Rabat

Davies-Vollum KS, Zhang Z, Agyekumhene A (2019) Impacts of lagoon opening and implications for coastal management: case study from Muni-Pomadze lagoon, Ghana. J Coast Conserv 23(2):293–301

De Wit R (2011) Biodiversity of coastal lagoon ecosystems and their vulnerability to global change. In: Grillo O, Venora G (eds) Ecosystems biodiversity. IntechOpen, Rijeka, pp 29–40

De Jonge VN, Pinto R, Turner RK (2012) Integrating ecological, economic and social aspects to generate useful management information under the EU Directives' "ecosystem approach." Ocean Coast Manag 68:169–188

Department of Water and Forestry (2008) Khenifiss National Park - development and management plan 2008–2013. Ministry of Agriculture, Maritime Fisheries, Rural Development and Water and Forests, Rabat

El Agbani MA, Ferkhaoui M, Bayed A, Schouten JR (1988) The Khnifiss Lagoon and adjacent waters: hydrology and hydrodynamics. In: Dakki M, De Ligny W (eds) The Khnifiss Lagoon and its surrounding environment (Province of La'yyoune, Morocco). Travaux de l'Institut Scientifique, Rabat, pp 18–27

El Mahrad B, Abalansa S, Newton A, Icely JD, Snoussi M, Kacimi I (2020) Social-environmental analysis for the management of coastal lagoons in North Africa. Front Environ Sci 8:37

Elbelrhiti H, Claudin P, Andreotti B (2005) Field evidence for surface-wave-induced instability of sand dunes. Nature 437(7059):720–723

Elbelrhiti H, Andreotti B, Claudin P (2008) Barchan dune corridors: Field characterization and investigation of control parameters. J Geophys Res Earth Surf 113:F02S15

Elliott M, Burdon D, Atkins JP, Borja A, Cormier R, De Jonge VN, Turner RK (2017) "And DPSIR begat DAPSI (W) R (M)!": a unifying framework for marine environmental management. Mar Pollut Bull 118(1–2):27–40

Erostate M, Ghiotti S, Huneau F, Jouffroy D, Garel E, Garrido M, Pasqualini V (2022) The challenge of assessing the proper functioning conditions of coastal lagoons to improve their future management. Sci Total Environ 803:150052

Gao BC (1996) NDWI - A normalized difference water index for remote sensing of vegetation liquid water from space. Remote Sens Environ 58(3):257–266

Green EP, Mumby PJ, Edwards AJ, Clark CD (1996) A review of remote sensing for the assessment and management of tropical coastal resources. Coast Manag 24(1):1–40
Hackney CT, Yelverton GF (1990) Effects of human activities and sea level rise on wetland ecosystems in the Cape Fear River Estuary, North Carolina, USA. In: Whigham DF, Good RE, Kvet J (eds) Wetland ecology and management: case studies. Springer, Dordrecht, pp 55–61
Hammada S (2007) Etudes sur la végétation des zones humides du Maroc: Catalogue et analyse de la biodiversité floristique et identification es principaux groupement végétaux. Dissertation, Mohammed V University
Hayes MO (1975) Morphology of sand accumulation in estuaries: an introduction to the symposium. In: Eugene Cronin L (ed) Geology and engineering. Academic Press, Massachusetts, pp 3–22
Imaz-Lamadrid MA, Wurl J, Ramos-Velázquez E (2019) Future of coastal lagoons in arid zones under climate change and anthropogenic pressure. A case study from San Jose Lagoon, Mexico. Resources 8(1):57
Kjerfve B (1986) Comparative oceanography of coastal lagoons. In: Wolfe DA (ed) Estuarine variability. Academic Press, Massachusetts, pp 63–81
Klemas V (2011) Remote sensing techniques for studying coastal ecosystems: an overview. J Coast Res 27(1):2–17
Kousksou T, Allouhi A, Belattar M, Jamil A, El Rhafiki T, Arid A, Zeraouli Y (2015) Renewable energy potential and national policy directions for sustainable development in Morocco. Renew Sust Energ Rev 47:46–57
Laignel B, Vignudelli S, Almar R, Becker M, Bentamy A, Benveniste J, Birol F, Frappart F, Idier D, Salameh E, Passaro M, Menende M, Simard M, Turki EI, Verpoorter C (2023) Observation of the coastal areas, estuaries and deltas from space. Surv Geophys 44(5):1309–1356
Lakhdar Idrissi J, Sarf F, El Mossaoui N, Orbi A, Hilmi K (2000) Etude pluridisciplinaire de la lagune de Khnifiss (Sud du Maroc). Rapport Trav Docum 108:114
Lakhdar Idrissi J, Orbi A, Zidane F, Hilmi K, Sarf F, Massik Z, Makaoui A (2004) Organization and functioning of a Moroccan ecosystem: Khnifiss lagoon. Rev Sci Eau 17(4):447–462
Lewison RL, Rudd MA, Al-Hayek W, Baldwin C, Beger M, Lieske SN, Jones C, Satumanatpan S, Junchompoo C, Hines E (2016) How the DPSIR framework can be used for structuring problems and facilitating empirical research in coastal systems. Environ Sci Policy 56:110–119
Liu J, Mason PJ, Bryant EC (2018) Regional assessment of geohazard recovery eight years after the Mw7.9 Wenchuan earthquake: a remote-sensing investigation of the Beichuan region. Int J Remote Sens 39(6):1671–1695
Mahanty MM, Mohanty PK, Pattnaik AK, Panda US, Pradhan S, Samal RN (2016) Hydrodynamics, temperature/salinity variability and residence time in the Chilika lagoon during dry and wet period: measurement and modeling. Cont Shelf Res 125:28–43
Mahapatro D, Panigrahy RC, Panda S (2013) Coastal lagoon: present status and future challenges. Int J Mar Sci 3(23):178–186
Mahé Y (1957) La houle sur la côte atlantique du Maroc. J Hydraul 4(1):71–78
Maicu F, Abdellaoui B, Bajo M, Chair A, Hilmi K, Umgiesser G (2021) Modelling the water dynamics of a tidal lagoon: the impact of human intervention in the Nador Lagoon (Morocco). Cont Shelf Res 228:104535
Makaoui A, Orbi A, Hilmi K, Zizah S, Larissi J, Talbi M (2005) Upwelling of the Moroccan Atlantic coast between 1994 and 1998. CR Geosci 337(16):1518–1524
Mejjad N, Laissaoui A, Fekri A, Benmhammed A, El Hammoumi O, Cherif EK (2020) Does human activities growth lead to biodiversity loss in the Moroccan coastal lagoons? A diagnostic comparison study. In: Proceedings of the 4th Edition of International Conference on Geo-IT and Water Resources 2020, pp 1–5 (Abstract book)
Ministry of Equipment and Transport (2010) Protection of the lagoon environment. Ministry of Equipment and Transport, Rabat
Morton RA (1994) Texas barriers. In: Davis RA (ed) Geology of Holocene Barrier Island systems. Springer, Berlin, pp 75–114
Nakhli S, Ghazi A (2008) Quels outils pour un développement durable des zones côtières marocaines. In: Proceedings of the international pluridisciplinary conference "The littoral: challenge, dialogue, action" - Lille, 16–18 January 2008, France
Nichols M, Allen G (1981) Sedimentary processes in coastal lagoons. In: Proceedings of Unesco/IABO Seminar: Coastal Lagoon Research, Present and Future, UNESCO Technical Papers in Marine Science 33, pp 27–80
Nichols MM, Boon JD (1994) Sediment transport processes in coastal lagoons. In: Kjerfve B (ed) Coastal lagoon processes. Elsevier, Amsterdam, pp 157–219
Nieblas MO, Rodríguez JHG, Illescas ÁRJ (1999) Modelación de la marea en el sistemalagunar Bahía Magdalena-Almejas, BCS, México. Oceánides 14(2):79–88
Nogueira J, Evangelista H, Bouchaou L, Moreira L, Sifeddine A, ElMouden A, Msanda F, Caquineau S, Briceño-Zuluaga FJ, Licínio MV, Mandeng-Yogo M, Mendez-Millan M, Cordeiro RC, Knoppers B, Moreira-Ramírez M, Martins R (2022) Coastal wetland responses to a century of climate change in northern Sahara, Morocco. Limnol Oceanogr 67(2):285–299
Orbi A, Nemmaoui M (1992) Fluctuation des vents et variabilité de l'upwelling le long de la côte Atlantique marocaine. Trav Doc INRH 75:50
Pérez-Ruzafa A, Marcos C, Pérez-Ruzafa IM, Pérez-Marcos M (2011) Coastal lagoons: "transitional ecosystems" between transitional and coastal waters. J Coast Conserv 15(3):369–392
Pérez-Ruzafa A, Pérez-Ruzafa IM, Newton A, Marcos C (2019) Coastal lagoons: environmental variability, ecosystem complexity, and goods and services uniformity. In: Wolanski E, Day JW, Elliott M, Ramachandran R (eds) Coasts and estuaries. Elsevier, Amsterdam, pp 253–276
Postma H (1969) Chemistry of coastal lagoons. In: Ayala-Castañares A, Phleger FB (eds) Coastal lagoons: a symposium. UNAM/UNESCO, Mexico, pp 421–430
Puente-Rodríguez D, Giebels D, De Jonge VN (2015) Strengthening coastal zone management in the Wadden Sea by applying 'knowledge-practice interfaces.' Ocean Coast Manag 108:27–38
Ranke U, Von Rad U, Wissmann G (1982) Stratigraphy, facies and tectonic development of the onshore and offshore Aaiun-Tarfaya Basin: a review. In: von Rad U, Hinz K, Sarnthein M, Seibold E (eds) Geology of the Northwest African Continental Margin. Springer, Berlin, Heidelberg, pp 86–105
Reed DJ, Cahoon DR (1992) The relationship between marsh surface topography, hydroperiod, and growth of *Spartina alterniflora* in a deteriorating Louisiana salt marsh. J Coast Res 8(1):77–87
Rouse JW, Haas RH, Schell JA, Deering DW (1974) Monitoring vegetation systems in the Great Plains with ERTS. NASA Spec Publ 351(1):309–317
Rozas LP (1995) Hydroperiod and its influence on nekton use of the salt marsh: a pulsing ecosystem. Estuaries 18(4):579–590
Saltani Z, Benmohammadi A, Belabed M (2015) Origine du phénomène d'ensablement déduite par combinaison entre télédétection et techniques sédimentologiques: application au bassin côtier de Tarfaya, sud-ouest marocain. Afri Sci 11(1):268–276
Samal RN (2011) The transport of sediments in Chilika lagoon, East Coast of India. Dissertation, Berhampur University
Tnoumi A, Angelone M, Armiento G, Caprioli R, Crovato C, De Cassan M, Montereali MR, Nardi E, Parrella L, Proposito M (2021)

Assessment of trace metals in sediments from Khnifiss Lagoon (Tarfaya, Morocco). Earth 2(1):16–31

Tnoumi A, Angelone M, Armiento G, Caprioli R, Crovato C, De Cassan M, Montereali MR, Nardi E, Parrella L, Proposito M (2022) Heavy metal content and potential ecological risk assessment of sediments from Khnifiss Lagoon National Park (Morocco). Environ Monit Assess 194(5):356

Toure S, Diop O, Kpalma K, Maiga AS (2019) Shoreline detection using optical remote sensing: a review. ISPRS Int J Geo-Inf 8(2):75