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Shoreline Changes at the Souss and Massa rivers mouths, Morocco: A five decades analysis (1970-2024)

M'hamed Nmiss [*1], Mhamed Amyay [1], Nadia Atiki [2], Abderrahman Ouammou [3] Mahjoub Benbih [3] Hassan Nait-Si [3], Mohammed Yazami Ztait[1], El Miloudiya Naji[4]

*[1] Sidi Mohamed Ben Abdellah University, Departement of Geography - FLSH Sais-Fez, Morocco, * mhamed.nmiss@usmba.ac.ma, mhamed.amyay@usmba.ac.ma, mohammed.yazamiztait@usmba.ac.ma*
[2] Abdelmalek Essaâdi University, Departement Geography - FLSH Tetouan, Morocco, natiki@uae.ac.ma
[3] Ibn Zohr University, Departement of Geography - FLSH Agadir, Morocco, ouammouabderrahmane@gmail.com, benbihelmahjoub@gmail.com, hassan.nait-si@edu.uiz.ac.ma
[4] Mohammed V University, Department of Geology, FS Rabat-Agdal, Morocco, elmiloudiya_naji@um5.ac.ma

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Abstract

River mouths are crucial environments for the exchange of energy and matter between land and ocean, yet they are highly sensitive to human interventions. This study analyzes the multi-decadal and seasonal dynamics of the Massa and Souss river mouths on the Moroccan Atlantic coast. Their evolution was assessed through diachronic shoreline analysis using aerial photographs and satellite images from 1970 to 2024, processed with GIS and DSAS tools. A seasonal topographic survey was also conducted in 2019–2020 on seven profiles using a total station. The results reveal contrasting trends: the Souss mouth is generally eroding, while the Massa mouth remains relatively stable with slight accretion. On a seasonal scale, topographic profiles indicate a morphological cycle of winter erosion followed by summer accumulation, maintaining a balanced sediment budget. Various natural and anthropogenic factors have shaped these changes over the past five decades. The river mouths experience intense Atlantic waves capable of eroding and redistributing sediments deposited by floods. Meanwhile, multiple upstream dams in the Souss and Massa watersheds have trapped 76.3 Mm^3 of sediments, significantly reducing downstream sediment supply. Despite this, at a seasonal scale, the morphodynamic balance seems maintained by potential sand sources compensating for the decline in fluvial sediment input. These findings highlight the importance of understanding the interactions between hydrodynamic processes and sediment transport in these coastal environments. This study provides key insights for planning and managing the Souss and Massa estuaries, serving as a scientific reference for developing protection and integrated management strategies for these ecologically and biologically vital environments.

1. Introduction

The mouths of rivers are highly dynamic, fragile, and constantly evolving environments [1,2]. They are subject to complex interactions between various hydrodynamic, sedimentological, and anthropogenic factors. The morphological evolution of these contact zones between land and sea results from a set of complex interactions involving swell, waves, tides, coastal currents, and the fluvial regime of the rivers [3,4]. Other factors, such as wind strength and local topography, also play a role in explaining the different changes affecting these areas. Furthermore, human activities, particularly the construction of upstream dams and the stabilization of river banks, can significantly influence the dynamics and evolution of river mouths [5-8].

In semi-arid to arid regions, such as Morocco, rivers mouths are characterized primarily by alternating closure phases, which can last several months or even years during dry periods, and episodic openings mainly linked to flood events [9-11]. This dynamic appears to be largely influenced by the interaction between river discharge and the prevailing wave conditions at the mouth, while strong winds and fluctuations in atmospheric pressure could also play a significant role [12]. These opening and closing phases have major repercussions on sediment management, ecological aspects, and water quality [13,14]. In recent years, research on the opening and closing dynamics of rivers mouths along the Moroccan coastline has largely focused on diverse approaches, primarily based on numerical and statistical models [9,11,15-17]. These studies have relied mainly on bathymetric surveys, numerical modeling of wave conditions, and Geographic Information Systems (GIS).

GIS has become one of the most effective tools for capturing the evolutionary state of a river mouth at a given moment [18]. These tools facilitate spatial data analysis and enable the production of detailed and accurate maps illustrating the dynamics and evolution of river mouths. They are particularly useful for analyzing their spatiotemporal dynamics, delineating accretion and erosion zones, and calculating various parameters and indices that measure coastal evolution [19-24]. In recent years, the use of GIS and high-resolution spatial data has become increasingly common for monitoring river mouth dynamics [25-31]. GIS, with its ability to acquire, compile, store, manipulate, analyze, and display georeferenced data [32-43], offers particularly well-suited tools for these environments, where multiple interactive components converge [44-49]. Moreover, high-resolution spatial data provide significant potential for tracking the evolution of rivers mouths, as they offer an extremely precise and clear view of the state of these mouths at the moment the images are captured. Although these ecological aspects have attracted considerable interest, particularly due to the impact of closure and opening phases on fish ecology, the mechanisms driving the morphological changes that trigger these phases remain poorly studied.

This article aims to study the morphological changes of the Souss and Massa river mouths along the Moroccan Atlantic coast (Figure 1 b). Several specific objectives have been defined in this study. First, a detailed analysis of the evolution of the Souss and Massa river mouths was conducted over more than half a century (1968–2024), highlighting the cycles of opening and closing of these mouths. Next, a seasonal monitoring of the morphology of the river mouths was carried out between 2019 and 2020 to estimate the volumes of sand displaced by different morphodynamic agents. To achieve these objectives, we adopted a multi-method approach based primarily on an in-depth diachronic analysis of the morphology of the river mouths at different spatiotemporal scales (long, medium, and short term) using the Digital Shoreline Analysis System (DSAS) integrated into ArcGIS. This analysis was based on high-resolution spatial data, such as aerial photographs and satellite images. It was further complemented by field measurements conducted using a total station.

2.Method and material

2.1 Study area

South of Agadir (30°N), the Moroccan Atlantic coast is characterized by a fragile semi-arid to arid environment, yet it displays remarkable morphological diversity, alternating between cliffs and extensive sandy beaches. The largest beaches are closely linked to two major hydrographic arteries: the Souss River in the north, which drains an 18,000 km^2 Atlas watershed and discharges into the bay of Agadir, south of the Royal Palace (Figure 1 b), and the Massa River in the south, which drains a 4,970 km^2 Anti-Atlas watershed (Figure 1 b). The Souss and Massa river mouths present contrasting characteristics in their interactions with the Atlantic Ocean. The Souss River mouth, extending 1 km, remains permanently open, forming an estuarine system that continuously discharges water into the ocean (Figure 2 a). In contrast, the Massa River mouth, which stretches 750 meters in a low-lying area (Figure 2 b), is typically closed and only opens sporadically during intense winter floods or controlled releases from the Youssef Ben Tachafine dam [50,51].

The mouths of the Souss and Massa rivers are designated integral protection zones within the Souss Massa National Park, an area of great ecological and environmental value. Classified as Ramsar wetlands in 2005, they are recognized as biological and ecological sites of national and international importance [44]. These wetlands host a rich diversity of migratory bird species, providing them with favorable conditions to spend a mild winter, far from the harsh cold of higher latitudes. The river mouths offer an ideal habitat for migratory birds, thanks to the abundant food resources, such as fish and aquatic invertebrates, as well as a peaceful refuge where they can rest and reproduce. Additionally, they play a crucial role as buffer zones between terrestrial and marine ecosystems, facilitating the exchange of matter and energy between these two environments. As Ramsar sites, the Souss and Massa river mouths benefit from enhanced protection and sustainable management aimed at preserving their ecological richness and cultural value. Conservation and awareness efforts are being implemented within the national park to protect these fragile wetlands and the species that depend on them.

Climatically, the Souss and Massa river mouths are subject to a Mediterranean-type climate, characterized by the alternation of a hot, dry season and a mild, wet season [52-54]. The annual average precipitation recorded at the two closest weather stations amounts to 213 mm at the Agadir station (located 5 km from the coast) and 163 mm at the Melk Zhar station (11 km from the coast) (Figure 1 b). These precipitations exhibit significant interannual and intra-annual variability. The average annual temperatures are 20.13°C in Agadir and 21.53°C in Melk Zhar. Regarding dominant winds in this coastal sector, they mainly blow from the west and northwest (Figure 3 c, d). Hydrodynamically, the Souss and Massa river mouths are highly exposed to energetic Atlantic waves from the NNW sector. Based on daily forecasts managed by the Spanish port authorities at SIMAR point 1040022 (coordinates 30.500°N, -10.000°E), 82.5% of waves have a significant height below 2.5 m, while 17.5% exceed 2.5 m (Figure 3 aI, aII). Regarding wave periods, 47.14% have a duration exceeding 10 seconds (Figure 1 bI, bII). This wave pattern highlights the dominance of a swell-driven regime in winter and a mixed fair-weather wave regime with shorter-period waves in summer [55].

Hydrologically, the Souss and Massa rivers exhibit a highly variable flow regime, characterized by rare or even nonexistent surface flow, except during winter floods. To analyze their flow regime and discharge, data from two hydrological stations were considered (Figure 1 b). The Youssef Ben Tachafine Dam (BYBT) station on the Massa River, located 34 km upstream from the mouth, monitors a 3,970 km^2 area, covering 79% of the Massa watershed (Figure 1 b). The Aït Melloul station on the Souss River, located 12 km upstream from the mouth, monitors a 16,000 km^2 area, representing 88% of the Souss watershed (Figure 1 b). During the observation period (1976-2018), the mean annual discharge was 3.91 m^3/s at the BYBT station and 8.05 m^3/s at the Aït Melloul station. Since the 1970s, river discharge has been regulated by the construction of multiple dams on the Souss and Massa rivers and their tributaries. These include the Youssef Ben Tachafine and Ahl Souss dams in the Massa basin, as well as the Aoulouz, Mokhtar Soussi, Imi El Kheng, Abdelmoumen, and Dkhila dams in the Souss basin (Figure 1 b)

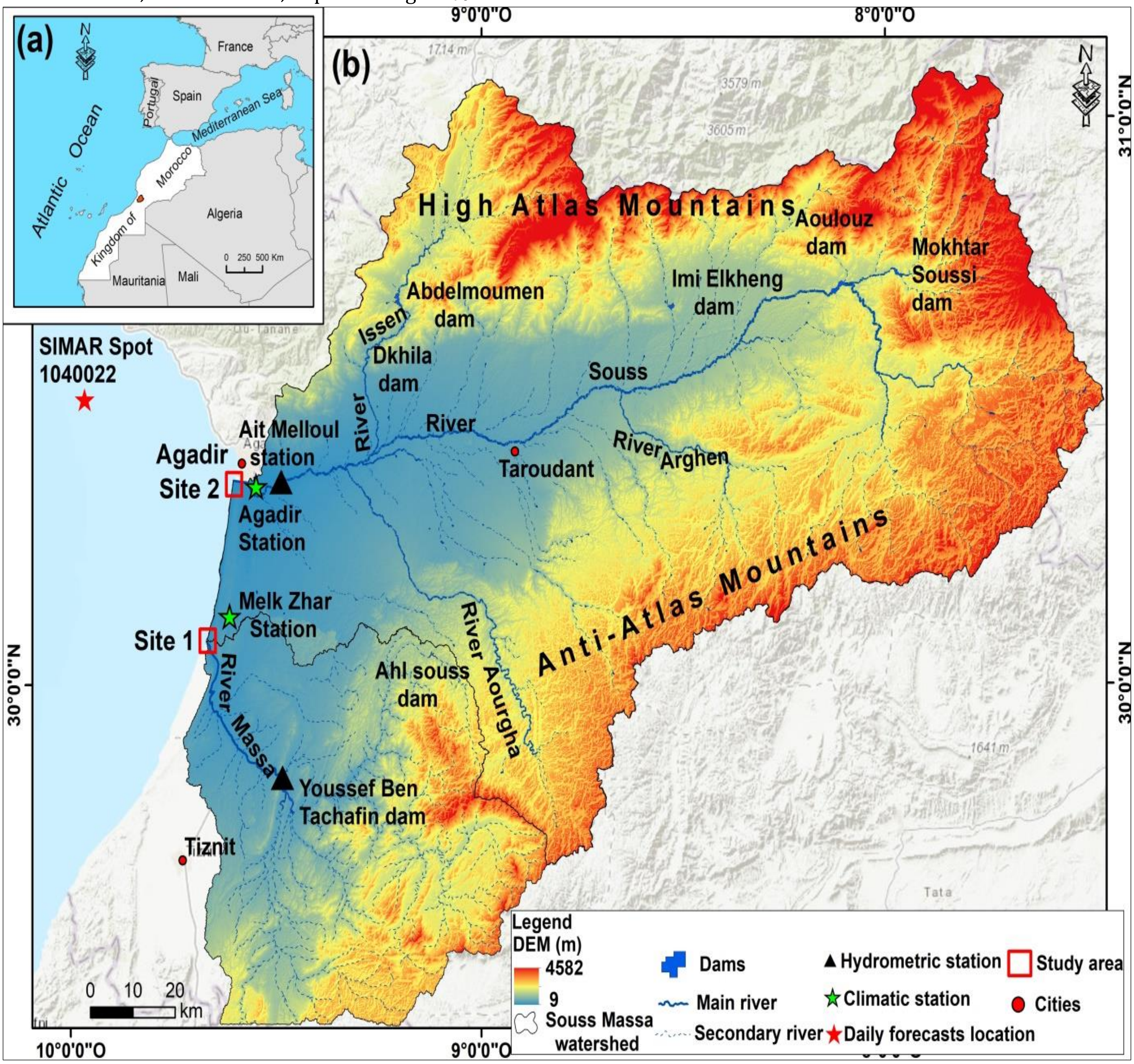

Figure 1. Location of the study area. (a) Overview of the study area on the map of Morocco; (b) Location of the study sites within the Souss and Massa watersheds (Source: Digital Elevation Model, https://earthexplorer.usgs.gov/).

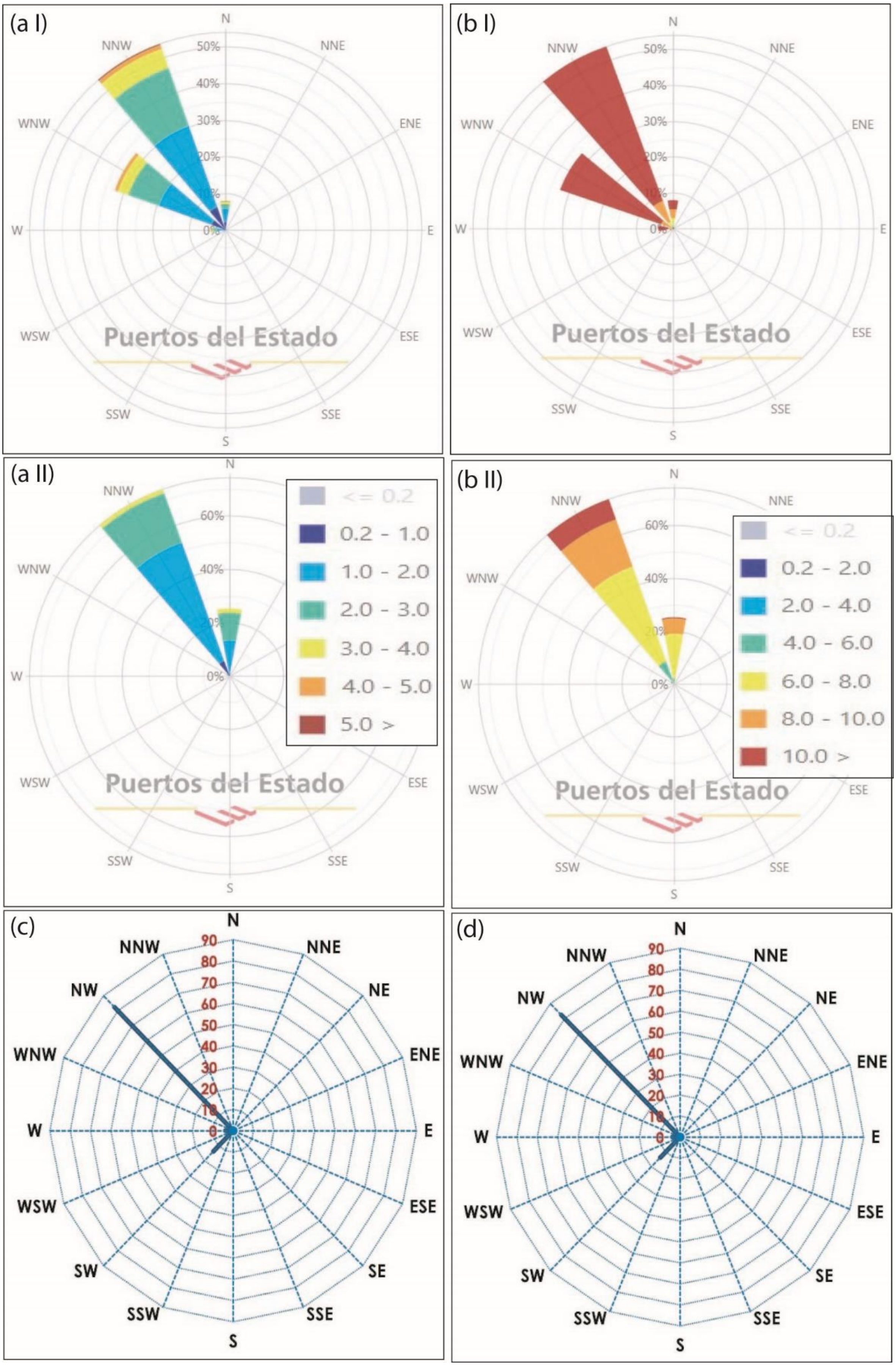

Figure 3. Dominant hydrodynamic conditions along the Souss-Massa coastline.(a I) and (a II) Significant wave height roses from SIMAR point 104022 for the period 1958-2024 (Fig. 1b); (a I) represents the winter period; (a II) represents the summer period.(b I) and (b II) Wave period distribution (1958-2024), with (b I) for the winter season and (b II) for the summer season (source: https://portus.puertos.es).(c) Dominant wind direction at the Agadir station for the period 1997-2016 (Fig. 1b).(d) Dominant wind direction at the Melk Zhar station for the period 1981-2016.

Figure 2. Studied sites. (a) Massa River mouth in an open state in 2017. (b) Souss River mouth.

To characterize the morphological variations of the Souss and Massa river mouths, we adopted a multi-scale approach combining several analysis methods. This approach is primarily based on long-term monitoring through photo-interpretation, allowing us to analyze the morphological evolution of the river mouths over several decades. Additionally, seasonal monitoring was conducted using precise topographic measurements with a total station to quantify short-term morphological changes.

2.2 Multi-Decadal Shoreline evolution (1968-2024).

To detect the evolution and dynamics of the Souss and Massa river mouths over more than half a century (56 years) from 1968 to 2024, we relied on high-resolution spatial data. These include aerial photographs from the 1970s, 1986, and 2015, as well as satellite images from Google Earth Pro and the Pléiades satellite (Table 1). Although these data provide only snapshot representations, their comparison highlights different phases of the geomorphological evolution of the shoreline [10,19,22,55]. The analysis and processing of these spatial sources were carried out using digital image processing techniques. This approach follows the method adopted by Theiler and Danforth [56], which involves georeferencing satellite images, correcting distortions and transformations, digitizing features, and performing a diachronic overlay of successive shoreline positions. We selected the instantaneous shoreline as the reference line to determine the morphological changes in the river mouths. This line corresponds to the intersection between the sea surface, deformed by tidal waves, and the slope of the foreshore at the time of recording [57]. While easily identifiable in all documents, it depends on the meteorological and marine conditions preceding the survey dates. The choice of this line over the high-water line, which is widely used in the literature [58,23,24], is justified by the high dynamics and complexity of river mouth zones, where tidal penetration significantly influences the lower reaches of the fluvial system.

Table 1. Spatial data used to monitor the dynamics of the river mouths.

Spatial data	Date of shoreline extraction	Scale (aerial photos) and resolution (satellite images	Season Period	Source
Aerial photography	November 14, 1970	1/ 30000	Autumn	National Agency of Land Conservation
	March 22, 1986	1/ 20000	Intermediate (Hiver Spring)	Cadastre and Cartography, technical documentation
Orthophotography	May 28, 2015	1/5000	Spring	service

	January 25, 2024		Winter	Google Earth Pro
	March 28,2023		Spring	
Satelitte images		1 m		
	April 27, 2021		Spring	
	October 24, 2020		Autumn	
Pleiades orthophotography	October 29, 2018	0.5 m	Autumn	Cartographic Department of the Urban Agency of Agadir
	September 12,2016		Summer	
	May 28, 2015		Spring	
Satelitte images	December 01,2012	1 m	Summer	Google Earth Pro
	June 20, 2009		Summer	
	March 01, 2003		Winter	

To quantify the geomorphological evolution of the shoreline at the Souss and Massa river mouths, we relied on the DSAS (Digital Shoreline Analysis System) application, an add-in for ArcGIS. This application was developed to determine the historical shoreline change rate using a series of shorelines from different dates [56, 53]. It allows users to calculate shoreline change rate statistics over a chronological series of different shoreline positions [53]. The principle of DSAS is primarily based on creating transects along the coastline from a reference line called the "Baseline." The intersection of these transects with the shorelines enables the calculation of two key parameters. The first is NSM (Net Shoreline Movement), which indicates the distance between the oldest and most recent shoreline for each transect. The second is EPR (End Point Rate), calculated by dividing the shoreline displacement distance between the first and last measurements by the number of years.

From a methodological perspective, it is essential to consider multiple sources of uncertainty that may affect the results of the diachronic analysis. These uncertainties primarily concern the quality of the aerial photographs and satellite images used for monitoring, the accuracy of data georeferencing, shoreline extraction, default parameters of the DSAS tool, as well as variations related to tidal conditions and the season at the time of image capture [61-65]. Regarding the margin of error associated with image quality, it is ±0.6 m. The georeferencing margin of error is ±1.7 m. For shoreline extraction, the margin of error is ±2.5 m, a value determined after multiple repetitions of coastline digitization. Concerning the uncertainty of the default data in the DSAS tool, the U.S. Geological Survey (USGS) suggests a default value of 10 meters. This value corresponds to the approximate average uncertainty associated with different types of shoreline data used in recent regional reports published by the USGS as part of the National Assessment of Shoreline Change project [60]. For variations related to tidal conditions, the margin of error is +58.86 m. This value was calculated based on the slope of the profiles (θ) and the water height (h) using the following formula: $\Delta d = h / \tan(\theta)$ [66].

The total uncertainty (UT) is calculated as the square root of the sum of the individual uncertainties [67]. By summing the relative margin of error due to quality of the data (± 0.6), georeferencing RMS (± 1.7 m), shoreline extraction (± 2.5 m), default data uncertainly of DSAS (±10) and the variation in the reference line position (high-water line) (± 58.86 m), we obtain an overall margin of error of approximately ± 8.86 m for the period 1968–2023, resulting in an annual error of ± 0.16 m/year.

2.3 Seasonal morphological evolution (2019-2020)

The monitoring of morphological evolution at a seasonal scale at the mouths of the Souss and Massa rivers was carried out using a high-resolution SOUTH NTS-375R electronic total station (with an accuracy of approximately ±1.5 mm according to the manufacturer's specifications). This station operates by targeting a reflective staff, held by an operator positioned at the measurement point [50,68].In total, seven topographic profiles were established, including five at the Massa river mouth and two at the Souss river mouth (Figure 4 a, b). It is important to note that these profiles were conducted both perpendicular to the shoreline and transversely, connecting both banks of the river. At the Souss river mouth, particular emphasis was placed on the left bank, located within the boundaries of the Souss-Massa National Park, as access to the right bank is restricted due to its inclusion within the royal palace domain.

The topographic surveys were conducted between January 2019 and July 2020, with seasonal repetition (winter/summer). The selection of these two seasons for the surveys aimed to observe the response of these complex environments to energy peaks, which are particularly pronounced in winter and summer, as opposed to the transitional seasons (autumn and spring). Another objective was to study the annual morphological cycle at the river mouths.

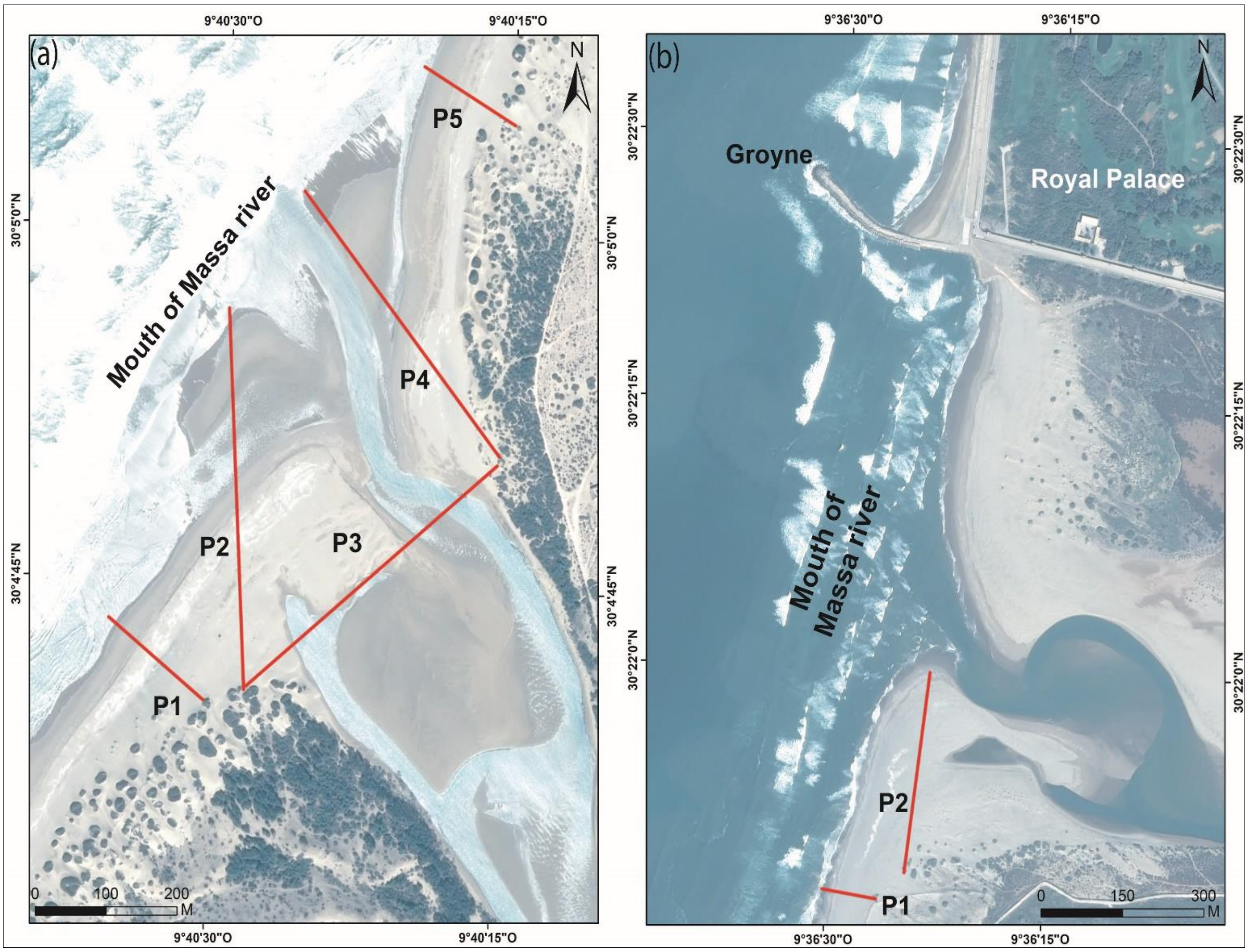

Figure 4. Location of topographic profiles surveyed between 2019 and 2020 at the mouths of the Massa and Souss rivers.

Table 2. Measurement Dates and Field Missions Conducted at the Mouths of the Massa and Souss Rivers.

Measurement mission	Date of measurement	Mouth of Massa					Mouth of Souss	
		P1	P2	P3	P4	P5	P1	P2
Mission I	07/01/2019	X	X	X	X	X		
	09/01/2019						X	X
Mission II	13/09/2019	X	X	X	X	X		
	16/09/2019						X	X
Mission III	09/02/2020	X	X	X	X	X		
	14/02/2020						X	X
Mission IV	10/07/2020	X	X	X	X	X		
	14/07/2020						X	X

3.Results

3.1 Multi-decadal shoreline evolution

3.1.1 The mouth of Souss river

The monitoring of the dynamics and evolution of the Atlantic river mouths of Massa and Souss over five decades reveals a highly marked spatiotemporal evolution. At the mouth of the Souss river, the results obtained show a complex and heterogeneous evolution of the shoreline between 1970 and 2024. Data analysis indicates a general trend of erosion, although the intensity and spatial distribution of this phenomenon vary considerably over time. The asymmetry observed between the left and right sides of the river mouth, as well as the local influence of structures such as groynes, highlight the need for a nuanced approach to understanding the underlying mechanisms.

Over a 54-year period (1970-2024), the general trend is shoreline erosion and retreat on both banks of the Souss river (Figure 5). The highest rate of change is recorded on the right bank, with a value of -297 m, corresponding to an annual retreat of -5.5 m/year. In contrast, on the left bank, the shoreline retreat gradually decreases southward, reaching -37 m, or an annual retreat of -0.68 m/year (Figure 7). The period from 1970 to 1986 is characterized by particularly intense erosion, especially on the right bank of the river mouth. The shoreline retreat is significant, reaching up to -123 m, or -7.68 m/year, indicating a substantial loss of land. Accumulation, on the other hand, remains limited and localized, suggesting an imbalance between erosion forces and sediment supply. Shoreline advancement is observed on the left bank, with a maximum value of +47 m, or +2.9 m/year. At the southernmost part of the left bank, shoreline stability is noted, with nearly no significant change. Subsequently, between 1986 and 2003, the general trend remains one of erosion on the right bank, although some areas of accumulation exist, particularly at the southern end of the left bank. The maximum shoreline retreat reaches -82 m, or -4.8 m/year, on the right bank. However, a maximum accretion of +22 m is recorded on the left bank of the River (Figure 7).

Between 2003 and 2009, shoreline monitoring indicates more pronounced erosion on both banks of the Souss River, despite localized accumulation that remains insufficient to compensate for losses. The maximum retreat rate reaches -70 m, equivalent to -11 m/year. This trend intensifies during the period 2009-2016, with more severe erosion on both banks of the river mouth and increased accumulation at the northern end of the mouth, on the right bank. The maximum retreat rate for this period is -85 m, or -12.14 m/year. In the northern sector (right bank), particularly north of the groyne, the maximum shoreline advance is 38 m, or 5.4 m/year (Figure 7).

Furthermore, the period 2016-2018 indicates a shift towards accretion on both banks of the river, although some erosion zones persist. Pronounced accumulation is particularly noticeable on the left bank of the Souss River, with a maximum advance of 133 m. Additionally, the following years (2018-2021) show a slight slowdown in erosion on the right bank and the beginning of accumulation, especially on the left bank. During this period, a comparison between Pléiades images and Google Earth Pro images indicates moderate erosion on the right bank, with a maximum retreat of -70 m. In contrast, shoreline stability dominates on the left bank during this monitoring period. Finally, shoreline evolution between 2021 and 2024 shows a certain equilibrium, with alternating zones of erosion and accumulation. Accumulation zones are located at the northern and southern extremities of the river mouth, where the shoreline advance reaches approximately 40 m.

3.1.2 The mouth of Massa river

The diachronic study of the shoreline at the mouth of the Massa River over a 53-year period (1970-2023) has allowed us to monitor the evolution and dynamics of the river mouth at different spatial and temporal scales. The results show that the Massa River mouth exhibits a complex and variable dynamic throughout the period from 1970 to 2023 (Figure 6). Unlike the Souss River, the analysis of spatial data, such as aerial photographs and satellite images, reveals a general trend toward accretion and sedimentary equilibrium, although this trend is punctuated by phases of localized erosion and periods of shoreline stability. The assessment of the evolutionary state of the Massa River mouth over the past five decades indicates a succession of opening and closing phases, as well as a shift in the river mouth location corresponding to the opening phases (Figure 6). Before the construction of the Youssef Ibn Tachafine dam upstream, the Massa River overflowed further north (Figure 6).

Shoreline monitoring between 1970 and 2023 indicates an overall trend toward accretion and stability. During this period, the results show a maximum shoreline advance of 234 m, or 4.41 m/year, on the right bank (Figure 8). This trend continues during the period 1970-1986, which is marked by particularly significant accumulation, characterized by a shoreline advance of more than 200 meters in certain areas. This widespread accumulation, observed on both sides of the river mouth, suggests abundant sediment supply and the environment's ability to retain these sediments. Shoreline advancement continues from 1986 to 2003, although at a slower rate, with some areas showing stabilization or even slight retreat. However, the period from 2003 to 2012 contrasts sharply with the previous ones, as significant erosion occurs, particularly on the right bank of the river mouth. The shoreline retreats notably, with erosion values reaching up to -70 meters, indicating a phase of sediment loss (Figure 8).

Between 2012 and 2015, the situation appears transitional, with limited accumulation. A comparison of aerial photographs from 2015 with satellite images from Google Pro indicates limited erosion on both banks of the river, corresponding to the opening phase of the river in 2015. However, at the northern and southern extremities of the river mouth, shoreline advancement is observed.

Subsequently, a strong accumulation occurs during the period 2015-2018, with a significant shoreline advance. This trend continues into the period 2018-2020, although localized erosion zones persist. Finally, the period from 2020 to 2023 shows shoreline advancement on the right bank and erosion on the left bank (Figure 8).

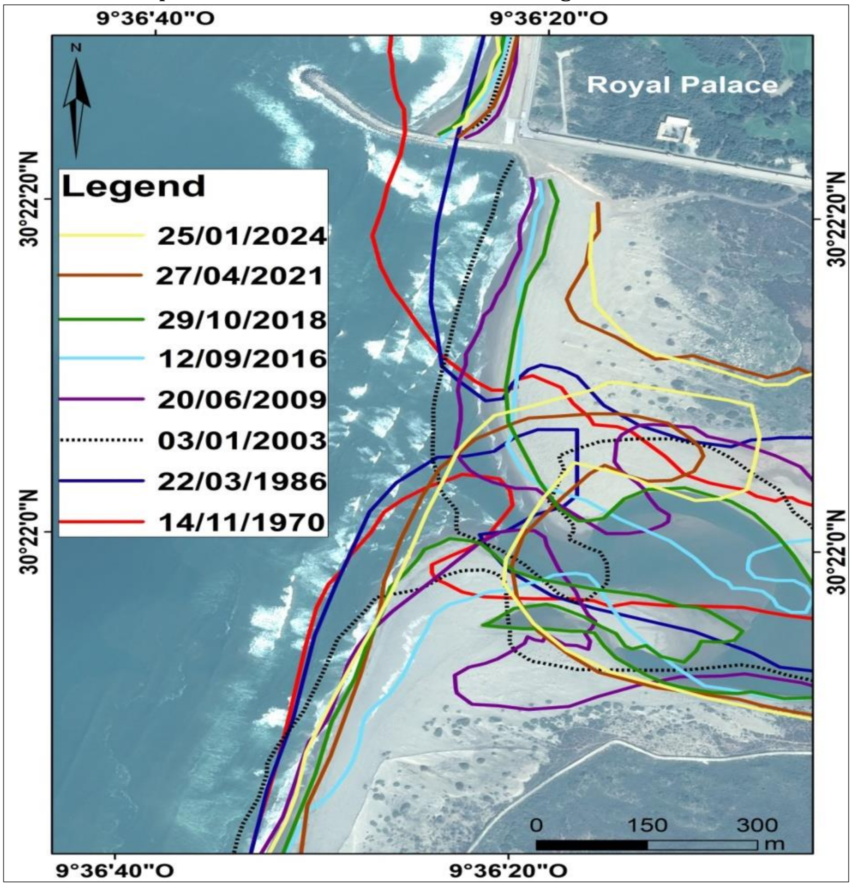

Figure 5. A highly complex evolution of the digitized shorelines based on all spatial data used at the Souss River mouth over a 54-year scale.

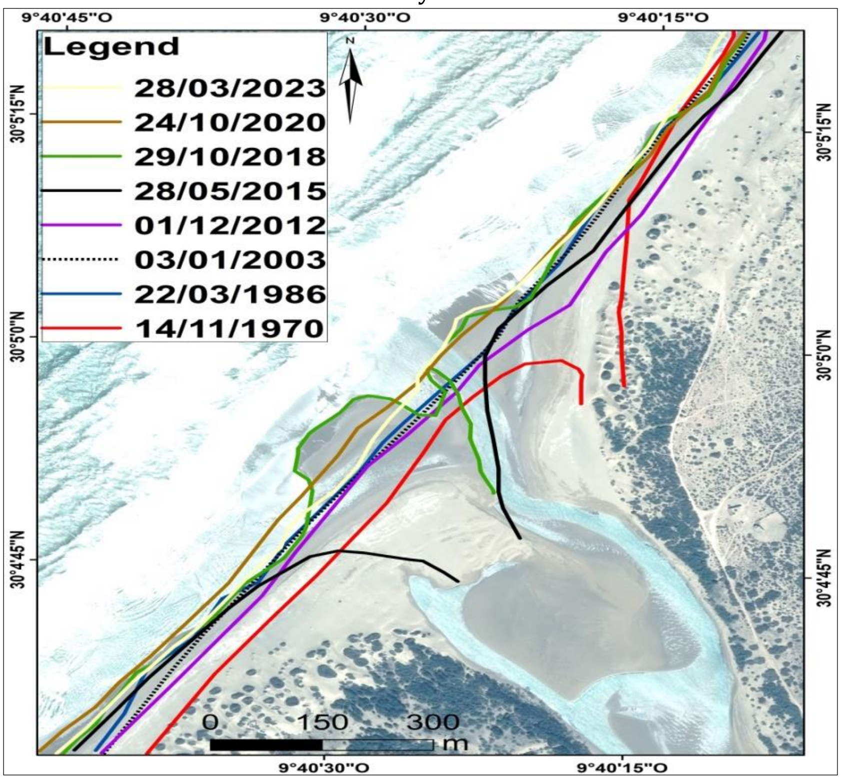

Figure 6. A highly complex evolution of the digitized shorelines based on all spatial data used at the Massa River mouth over a 53-year scale.

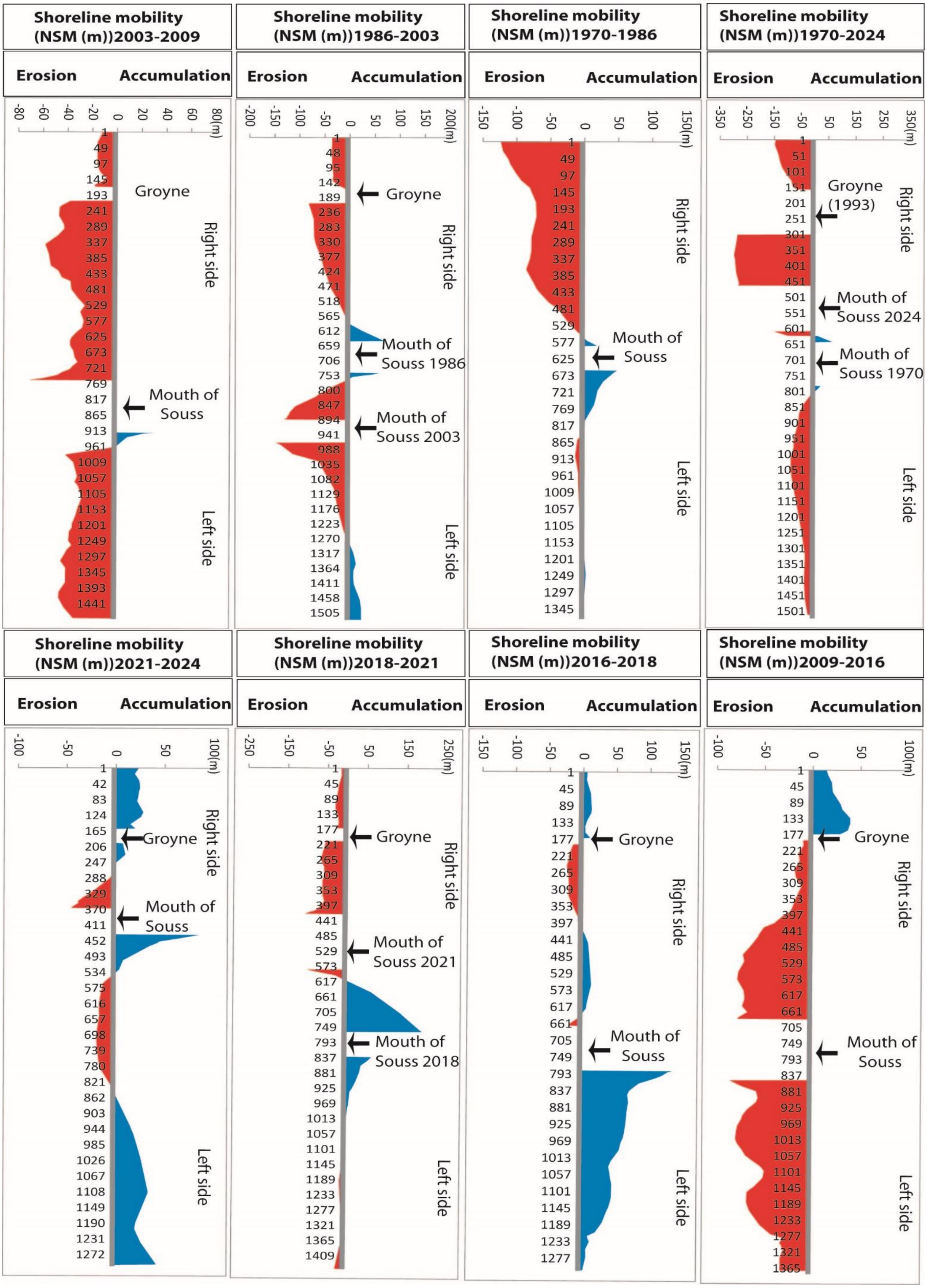

Figure 7. Overall evolution of both banks of the Souss River mouth (Net Shoreline Movement) at different time intervals.

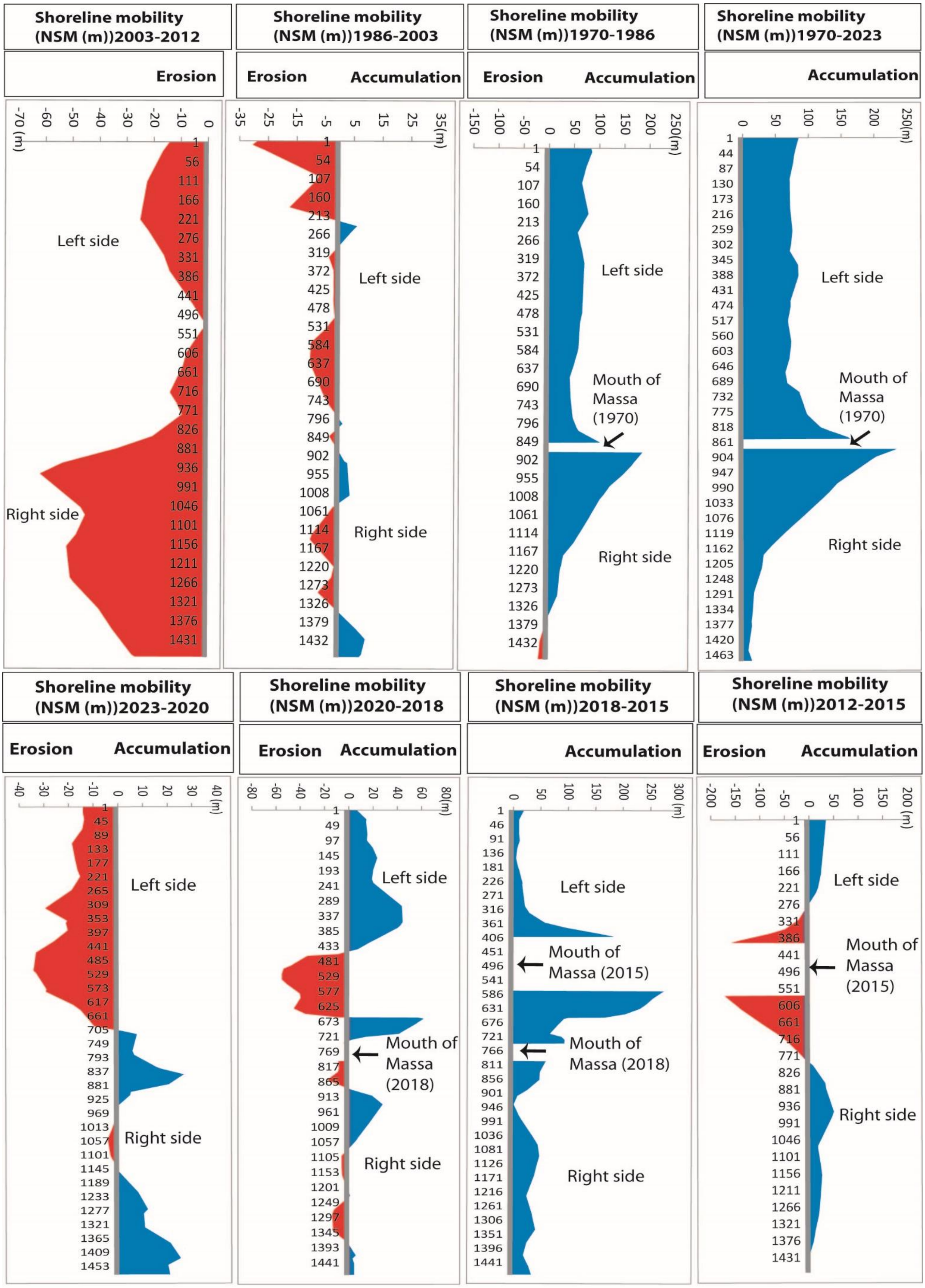

Figure 8. Overall evolution of both banks of the Massa River mouth (Net Shoreline Movement) at different time intervals.

3.2 Seasonal morphological evolution

The topographic monitoring of 7 profiles surveyed at the mouths of the Massa and Souss Rivers between January 2019 and July 2020 allowed us to monitor the dynamics of these complex environments on a seasonal scale. The profiles were surveyed both perpendicular to the shoreline and transversely, connecting both riverbanks. The results show a well-defined seasonal evolution and a clear morphological change between the winter and summer seasons (Figure 9). Across all the surveyed profiles, the morphological response of the Massa and Souss river mouths to the seasonal marine and wind energy extremes is characterized by a marked accretion during the summer seasons (January 2019 and July 2020) and progressively more pronounced erosion during the winter seasons. Indeed, the hydrodynamic factors prevailing during the winter seasons, such as swell, waves, tides, and coastal currents, smooth out their traces on the shape of the different profiles, manifesting as erosion across all profiles. Additionally, wind dynamics also play a significant role in the sediment displacement during the winter seasons. In contrast, the hydrodynamic factors predominant in the summer seasons favor significant sand accumulation across all the surveyed profiles (Figure 9).

The calculation of the sedimentary balances recorded during the winter and summer seasons allowed us to quantify the sediment inputs and losses observed in each profile. The results obtained are summarized in Figure 9 below. On a seasonal scale, the sedimentary balances clearly illustrate the influence of seasonal hydrodynamic impacts on the volumetric variations of sand. Across all the surveyed profiles, the sedimentary balance calculations show a certain morphodynamic equilibrium, even a trend toward accretion. The transition from January to September 2019 and February to July 2020 shows a positive sedimentary balance, varying from profile to profile, oscillating between +1 m^3/m and 0.1 m^3/m. On the other hand, the transition from September 2019 to February 2020 reveals a negative sedimentary balance, with values ranging from -0.6 to -0.1 m^3/m (Figure 10).

4.Discussion

5.1 A Complex Dynamics of the River Mouths on a Multi-Decadal Scale

The monitoring of the dynamics and evolution of the Atlantic river mouths of Massa and Souss over a period of 54 years has allowed for the tracking of morphological changes as well as the processes of opening and closing of these river mouths over time. The use of GIS, through the DSAS application, has also enabled the quantification of the advance and retreat of the shoreline along the riverbanks, as well as the identification of erosion and accumulation zones. The results reveal a highly complex and contradictory evolution of the river mouths of Massa and Souss on a multi-decadal scale. This evolution is marked by a tendency towards erosion and shoreline retreat at the Souss river mouth, and a trend towards accretion and stability at the Massa river mouth. Several factors can explain this contradictory evolution.

Regarding the Souss river mouth, coastal developments on the right bank, in front of the royal palace, have influenced the evolution and dynamics of the river mouth. Notably, a 326-meter-long groin constructed in 1993 was part of the coastal defense system aimed at combating erosion. While this defense structure has played a significant role in promoting local sediment accumulation in front of the royal palace, it may have done so at the expense of the southern sectors of the Souss river mouth. A comparison of aerial photos from the 1970s and 1986, prior to the construction of the groin, with satellite images illustrates the impact of the groin on both riverbanks (Figure 11 c, d, e, f).

A detailed analysis of aerial photos and satellite images from different dates has revealed the dynamics of the Souss river mouth over a chronological series of different dates. Aerial photos from the 1970s and 1986 (Figure 11 a, b) show the river mouth in a more natural state, as no visible artificial structures are present. However, satellite images from 2009, 2016, 2018, and 2024 show modifications to the natural dynamics of the river mouth, altering currents and deposition zones. Nevertheless, continuous sediment accumulation and changes in the morphological configuration of the river mouth continue, attesting to the combined influence of natural erosion-accretion processes and human interventions on the evolution of the river mouth.

Furthermore, the presence of a coastal spit at the Souss river mouth perfectly illustrates an active and directional sedimentary dynamic. Initially subtle in 1970 (Figure 11 a) , this sedimentary formation progressively developed towards the north over the decades, becoming increasingly pronounced in the 1986, 2009, 2016, and 2018 images, and reaching a significant extension by 2024 (Figure 11 f). Although the dominant wave direction, coming from the north or northwest, should theoretically induce a southward longshore drift, the shape of the spit observed in images (a) and (b), taken prior to the construction of the groyne, instead suggests a longitudinal sediment transport from south to north. This apparent contradiction can be explained by several factors. First, the incoming tidal currents (flood tide) can exert a significant, if not dominant, influence at the local scale of the Souss river mouth. A flood current coming from the south or southwest and flowing into the estuary can transport sediments northward along the left bank of the river mouth, thus contributing to the formation of the spit observed in the aerial images. Second, even waves approaching from the north may interact with tidal currents (especially the ebb tide) and with the specific morphology of the Souss river mouth. This interaction can generate complex circulation cells, creating local zones where the net sediment transport is reversed relative to the regional drift. Finally, the seabed topography (bathymetry) offshore and near the river mouth may cause significant wave refraction, even for waves coming from the north. Analysis of aerial photographs and satellite images reveals the presence of nearshore bars close to the Souss river mouth, located within the wave breaking zone. These underwater structures can alter the local wave approach angle, thereby inducing northward sediment transport over a short distance.

The Massa River mouth exhibits a general tendency towards shoreline accretion and stability, although transitional periods of erosion persist. Several factors can explain this fluctuating dynamic. The natural variability in sediment inputs from the Massa River, influenced by rainfall patterns and extreme climatic events, plays a determining role. In this regard, the presence of potential sources—such as well-developed coastal dunes and offshore sediment contributions—helps maintain the balance and stability of the Massa river mouth [10,50]. On a multi-decadal scale, the defining characteristic of the Massa river mouth is the alternation between phases of closure and opening over time. This dynamic is largely influenced by the river's hydrological regime. Before the construction of the Youssef Ibn Tachafine dam upstream in 1972, the Massa River mouth remained perpetually open (Figure 12 a). This situation is clearly visible in the 1970 aerial photo (Figure 12 a), where we observe that the river mouth was located even further north than it is today. Subsequent periods of opening correspond to times of flooding (Figure 12 c, d), while phases of closure are associated with periods of low river discharge (Figure 12 b). During these closure phases, the Massa river mouth is blocked by a sandbar that separates the river waters from those of the Atlantic Ocean, transforming the site from an estuarine system to a lagoonal one [69].

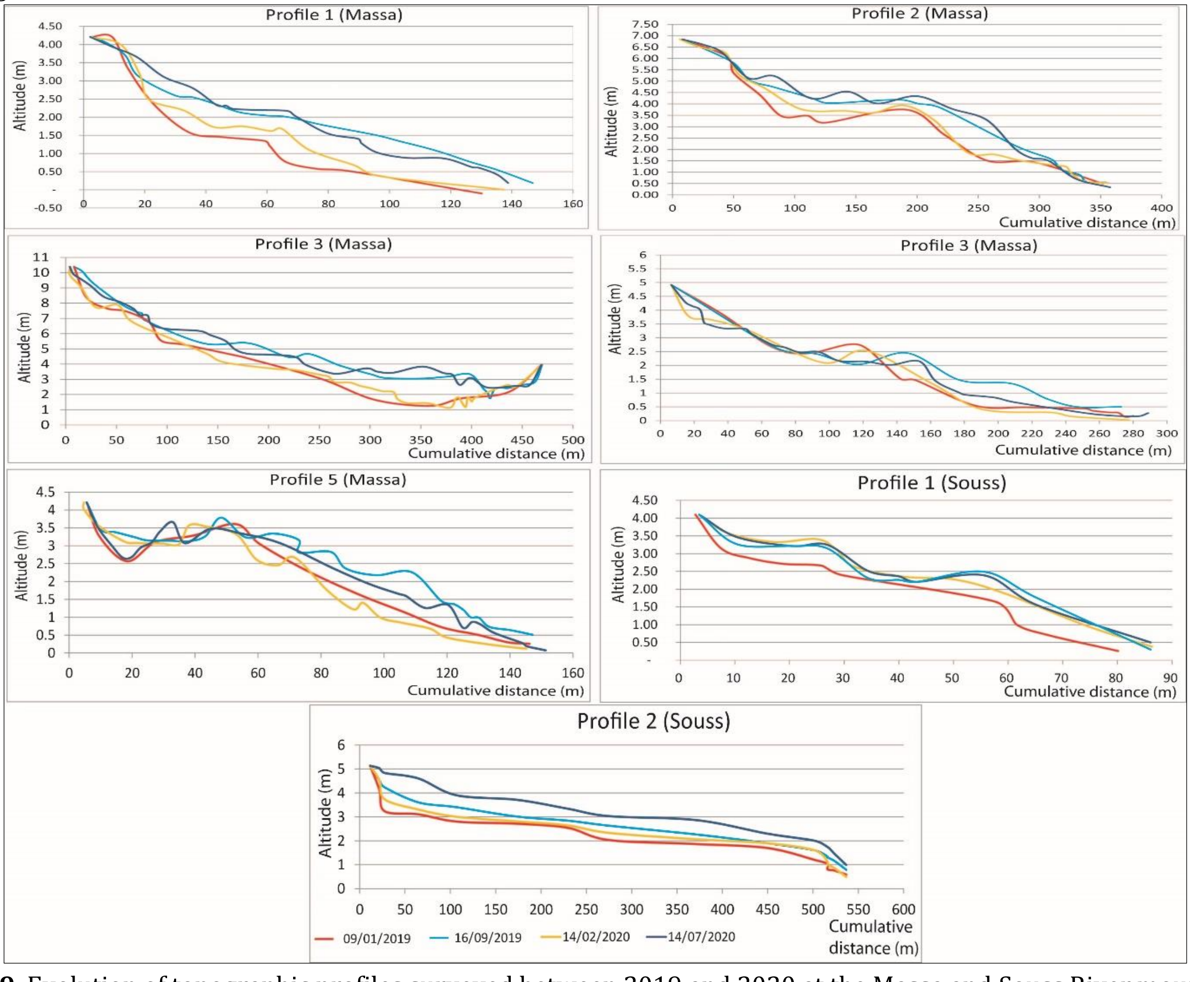

Figure 9. Evolution of topographic profiles surveyed between 2019 and 2020 at the Massa and Souss River mouths.

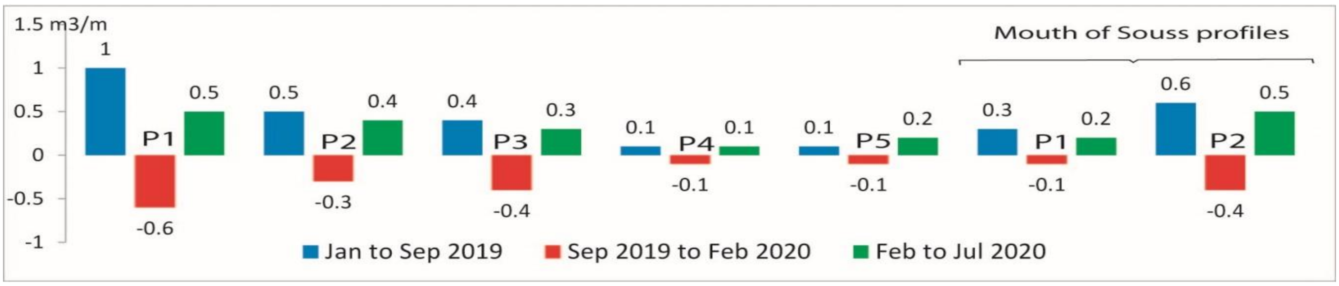

Figure 10. Sediment balance of all surveyed profiles showing the transition phases from the winter season to the summer season and vice versa.

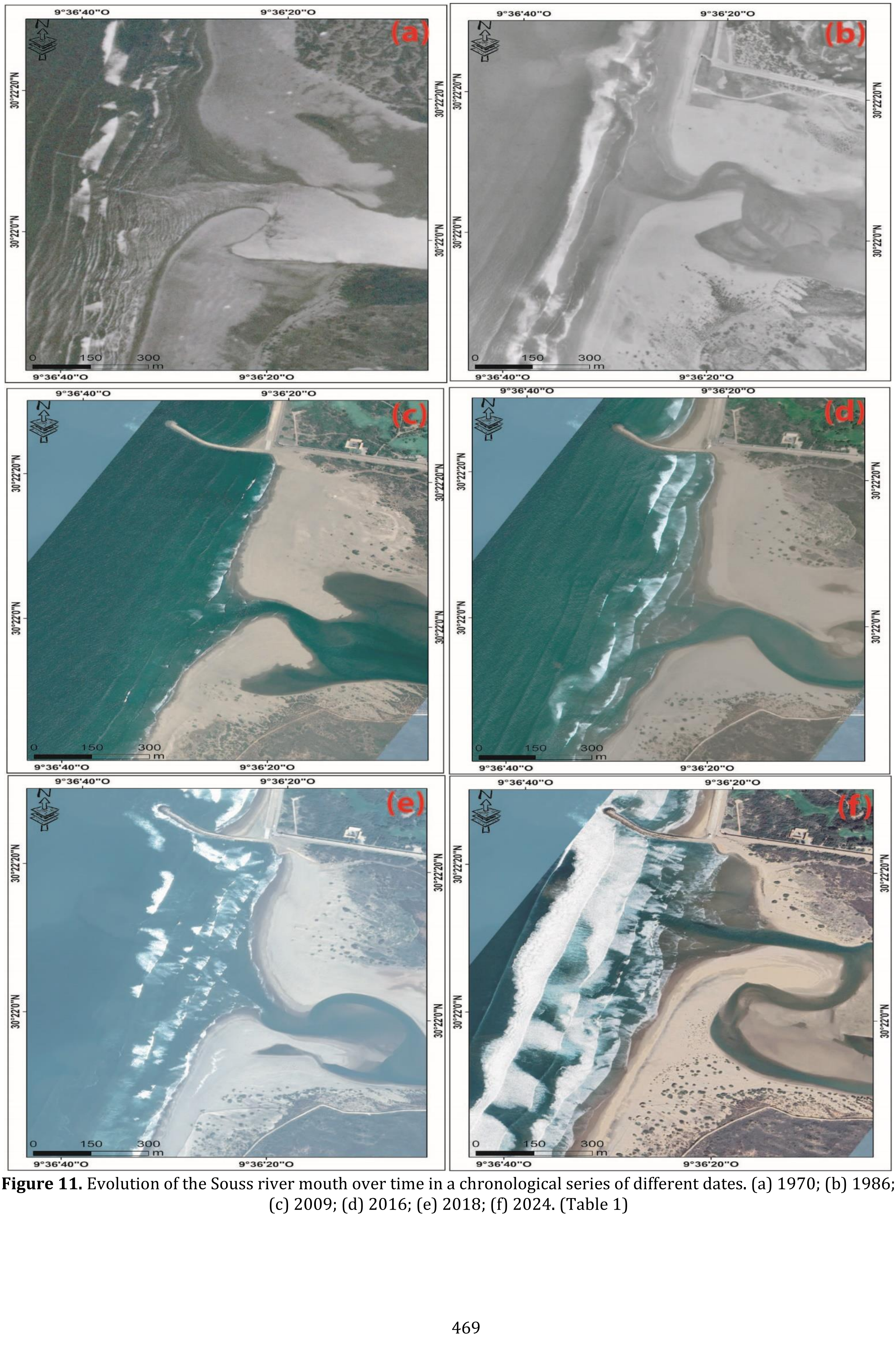

Figure 11. Evolution of the Souss river mouth over time in a chronological series of different dates. (a) 1970; (b) 1986; (c) 2009; (d) 2016; (e) 2018; (f) 2024. (Table 1)

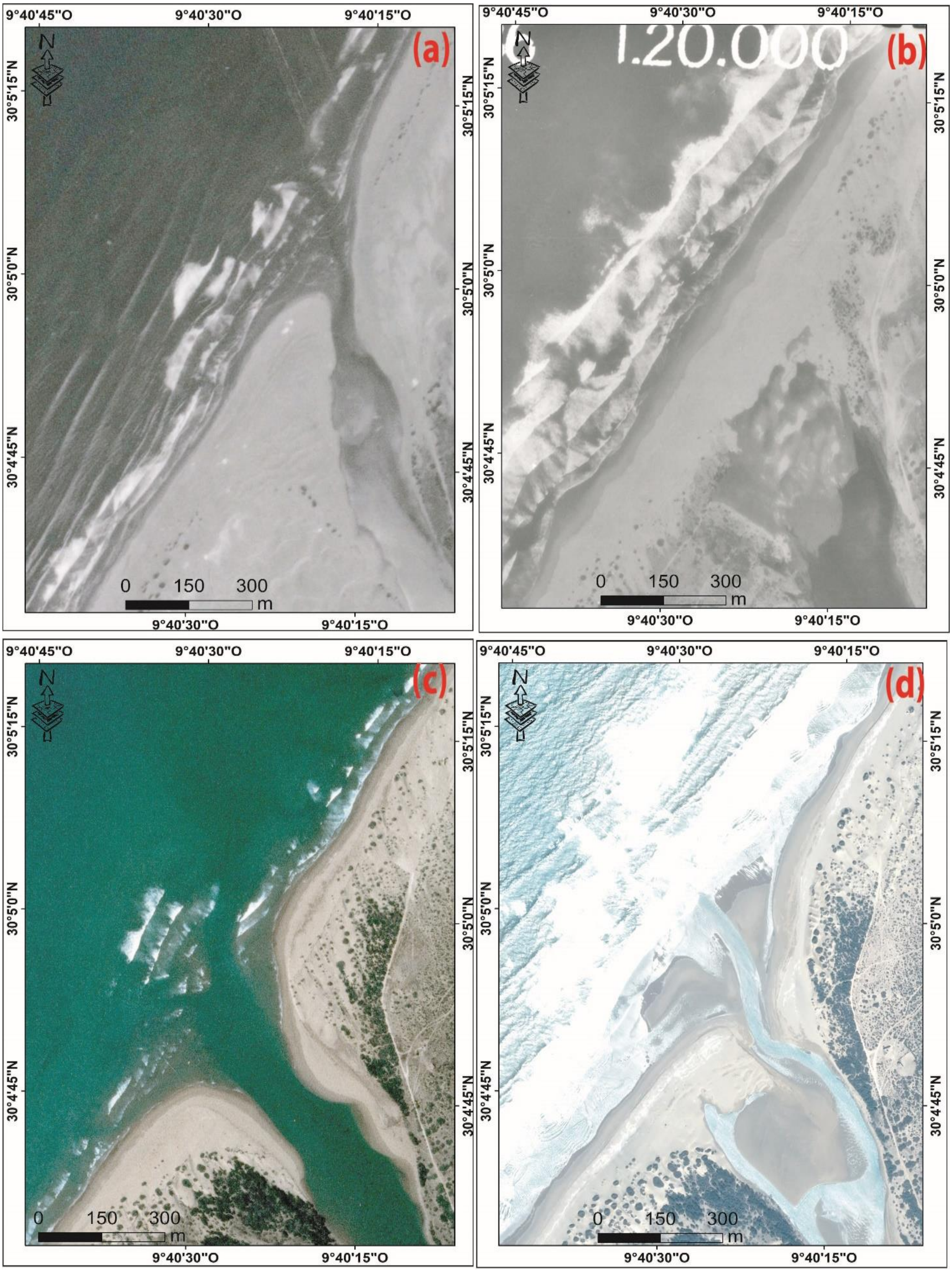

Figure 12. Evolution of the Massa river mouth over time in a chronological series of different dates. (a) 1970; (b) 1986; (c) 2015; (d) 2018 (Table 1).

Although the construction of dams on the main rivers in the Souss and Massa basins has fostered agricultural development in the region through the creation of several irrigated perimeters, it has also led to a reduction in river flow and, consequently, a decrease in terrigenous sediment input. To illustrate the rates of sediment trapped in the dams' reservoirs, we considered the sedimentation data from the reservoirs of the Souss and Massa basins. These include the Youssef Ibn Tachafine and Ahl Souss dams in the Massa basin, as well as the Aoulouz, Mokhtar Soussi, Imi Elkheng, Abdelmoumen, and Dkhila dams in the Souss basin (Figure 1 b). The sedimentation rate data for these hydraulic structures is summarized in Table 3 below. A straightforward interpretation of these data reveals a total sedimentation volume of 58.65 Mm^3 for the Souss watershed and 17.65 Mm^3 for the Massa watershed (Table 3). This indicates that 1.58 Mm^3/year of sediment has been trapped in the reservoirs of the Souss basin dams, and 0.38 Mm^3 in the Massa dams.

In recent decades, the impact of dams on the coastal evolution of the study area has become increasingly concerning, particularly due to the implementation of numerous hillside dams. While these hydraulic structures are crucial for flood control, they also cause significant sediment trapping. In a semi-arid to arid environment, these hydro-agricultural developments could jeopardize the ability of the rivers to supply the beaches with terrigenous sediments. Studies conducted in similar contexts, such as the Nile Delta in Egypt [70,71] or the Yunnan Province of southwest China coast [72], have highlighted comparable phenomena of reduced sediment flux to the shoreline, resulting in significant beach erosion. Likewise, research carried out along various Mediterranean and Atlantic coasts [71, 73-75] has shown that the construction of large dams has considerably decreased sediment supply to deltas, leading to accelerated coastal erosion a phenomenon particularly evident in Mediterranean environments with semi-arid climates. Additionally, the extraction of aggregates from various quarries located along the Souss River for use in the construction sector could also have a notable influence on the overall sediment budget of the coastline. This complex interaction between human interventions and natural processes raises questions about the sustainable management of these fragile environments and highlights the need to carefully consider the potential consequences of such actions on the delicate balance of coastal ecosystems.

Table 3. Siltation of the dams in the Souss and Massa watershed.

Dams Name	Commissioning date	Initial normal volume (Mm^3)	Normal volume from last bathymetry (Mm^3)	Date of last bathymetry	Lost volume (Mm^3)	Siltation rate (Mm^3/year)
Youssef ben Tachafine	1972	313.77	296.705	2017	17.07	0.4
Abdelmoumen	1981	222.00	198.436	2011	23.56	0.8
Dkhila	1986	0.716	0.178	2014	0.54	0.019
Aoulouz	1991	108.245	89	2017	19.25	0.7
Imi El Kheng	1993	12.00	9.113	2014	2.89	0.1
Mokhtar Soussi	2002	52.16	39.755	2011	12.41	1.4
Ahl Souss	2004	5.05	4.466	2014	0.58	0.1

4.2 A Balanced Sediment Budget on a Seasonal Scale

On a seasonal scale, the topographic monitoring of various surveyed profiles at the mouths of the Massa and Souss rivers indicates a balanced sediment budget between January 2019 and July 2020. The analysis of topographic profiles reveals a normal morphological cycle, characterized by pronounced erosion during winter surveys and accretion during summer surveys. The natural reconstruction of the Massa and Souss estuaries after erosion phases results from numerous feedback mechanisms that allow them to regain equilibrium even after severe storms. Thus, the existence of potential sand sources capable of supplying the estuaries even in cases of low terrigenous input explains this balance. These sources originate, on one hand, from offshore, due to the remobilization of sediment stocks from the continental shelf. This hypothesis has been extensively discussed along the Souss Massa coastline [10,50,51,58]and in other research studies[76-78] .On the other hand, sandy sediments also come from the bordering dunes adjacent to the river mouths. These dunes play a crucial role in maintaining the morphosedimentary balance of river estuaries on a seasonal scale [22]. They act as sand reservoirs capable of supplying these environments during sediment shortages. Furthermore, the Massa and Souss estuarine areas are sites of highly active aeolian dynamics. These areas channel winds from the W-E and NW-SE sectors, pushing deposited sands at the estuary towards the downstream sections of the rivers.

5.Conclusion

The study of the multi-decadal and seasonal evolution of the Massa and Souss river mouths through photo-interpretation and topographic monitoring has highlighted the dynamics of these complex environments located in a semi-arid to arid setting. On a multi-decadal scale (1970–2024), the results reveal a contrasting evolution between the two estuaries, characterized by alternating phases of closure and opening. The Souss river mouth, located south of Agadir, exhibits a dominant trend of erosion and shoreline retreat. In contrast, the Massa river mouth shows a trend toward accretion and stability. Several natural and anthropogenic factors explain these evolutionary trends. The shoreline retreat at the Souss river mouth is primarily linked to the construction of a coastal defense system in 1993 on the river's right bank to protect the Royal Palace of Agadir from erosion. This intervention has significantly influenced the evolution of the estuary over the past three decades. Furthermore, the construction of multiple upstream dams has considerably reduced sediment supply. Conversely, the stability of the Massa river mouth can be attributed to the presence of several sediment sources capable of maintaining the morphosedimentary balance, even in the event of a future decline in terrigenous input from the Massa River.On a smaller scale (2019–2020), the topographic monitoring of seven profiles reveals a normal morphological cycle, characterized by estuarine erosion in winter and sediment accumulation in summer. This seasonal alternation demonstrates the ability of these environments to restore eroded sediments transported offshore during winter seasons.

This study provides essential insights for planners and decision-makers by offering key elements for the preservation of these fragile environments, which hold significant environmental potential. The necessity of conservation becomes even more critical in a global context marked by climate change and rising sea levels. In this context, several recommendations can be formulated as part of this study: For the Souss river mouth, an ecological restoration approach should be considered. This may include the reconstitution of a sediment stock through controlled sand nourishment, the partial reconfiguration or targeted removal of rigid structures such as groynes that disrupt natural sediment transport, as well as the implementation of nature-based solutions, such as artificial reefs or vegetated dune ridges, to attenuate wave energy. It would also be relevant to initiate a reflection on the integrated watershed management of the Souss River, particularly by reassessing dam management practices to allow, where possible, for controlled sediment releases downstream. Concerning the Massa river mouth, although the current situation appears relatively stable, environmental monitoring measures should be implemented to prevent any future destabilization, particularly in the case of upstream hydraulic modifications or poorly planned coastal developments. The conservation of its lateral sediment inputs (such as cliff erosion and aeolian transport) should also be preserved. Finally, all of these recommendations should be part of a broader coastal resilience strategy that incorporates the objectives of combating the effects of climate and environmental change, by promoting flexible, sustainable policies grounded in natural dynamics.

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Author contributions

M'hamed Nmiss, Mhamed Amyay and abderrahmane Ouammou, Nadia Atiki: Conceptualization, Methodology, Field study, Writing-Original draft preparation, Data Analysis. **Mahjoub benbih, Hassan Nait-si, Mohamed Yazami Ztait, El miloudia Naji**: Data collection Data analysis, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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