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Reasearch article

Multidecadal evolution of the shoreline change at Agadir beach (Morocco): A GIS and high-resolution satellite imagery analysis

Evolução Multidecenal da Mudança da Linha de Costa na Praia de Agadir (Marrocos): Uma Análise com SIG e Imagens de Satélite de Alta Resolução

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Abstract: Beaches are extremely fragile and dynamic natural environments, where waves, coastal currents, and winds perpetually deposit and move sediments. The evolution of these beaches can only be envisaged by monitoring coastline dynamics at different spatiotemporal scales. In recent years, the use of high-resolution satellite images and GIS has become an indispensable tool for assessing beach evolutionary trends. In this contribution, we emphasize the importance of these new technologies for monitoring shoreline evolution on highly anthropized beaches, focusing on the case of Agadir beach on Morocco's Atlantic coast. A diachronic analysis of shoreline evolution was carried out over a period of 55 years extending from 1968 to 2023. This analysis is based on both high-resolution satellite images from various sensors (Corona, OrbView-3, Pleiades, WorldView-2) and the DSAS (Digital Shoreline Analysis System) tool integrated into ArcGIS©. The results obtained show a contrasting evolution, with a general trend towards erosion in the center and south of the beach, and an accentuated beach nourishment to the north. This trend is mainly attributed to the construction of a port complex (commercial harbour, fishing port, and marina) and to the various coastal developments undertaken on the beach.

Keywords: GIS, Satellite image, Agadir, Beach, DSAS.

Resumo: As praias são ambientes naturais extremamente frágeis e dinâmicos, onde as ondas, correntes costeiras e ventos depositam e movimentam sedimentos de forma contínua. A evolução dessas praias só pode ser compreendida por meio do monitoramento da dinâmica costeira em diferentes escalas espaço-temporais. Nos últimos anos, o uso de imagens de satélite de alta resolução e do SIG tornou-se uma

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ferramenta indispensável para avaliar as tendências evolutivas das praias. Nesta contribuição, destacamos a importância dessas novas tecnologias para o monitoramento da evolução da linha de costa em praias altamente antropizadas, com foco no caso da praia de Agadir, localizada na costa atlântica do Marrocos.Uma análise diacrônica da evolução da linha de costa foi realizada ao longo de um período de 55 anos, abrangendo de 1968 a 2023. Essa análise baseia-se em imagens de satélite de alta resolução de diversos sensores (Corona, OrbView-3, Pleiades, WorldView-2) e na ferramenta DSAS, integrada ao ArcGIS©. Os resultados obtidos mostram uma evolução contrastante, com uma tendência geral de erosão no centro e no sul da praia, e um acentuado aporte de sedimentos ao norte. Essa tendência é atribuída principalmente à construção de um complexo portuário (porto comercial, porto de pesca e marina) e aos diversos empreendimentos costeiros realizados na praia.

Palavras-chave: SIG, Imagem de satélite, Agadir, Praia, DSAS

1. Introduction

Sandy beaches constitute intricate and dynamic natural environments, subject to an array of hydrodynamic and anthropogenic factors that critically influence their morphological evolution. These shorelines are defined by the action of waves and littoral currents, which transport and deposit sediments larger than silt (Paskof & Clus-Auby, 2007). In recent decades, extensive research has underscored the global nature of sandy coast retreat, identifying it as a widespread phenomenon (Salman *et al.*, 2004; Gopinath *et al.*, 2005; Luijendijk *et al.*, 2018). This regression has intensified, driven largely by rising sea levels and diverse human interventions, including terrestrial sediment retention by dams (Amrouni & Mahé, 2021), aggregate extraction for construction (Temmler *et al.*, 2018), degradation of coastal dunes (Costa *et al.*, 2023), and the depletion of foreshore sandy reserves through dredging activities (Rangel-Buitrago & Neal, 2023). Studies focused on the region of Morocco's Atlantic coastline indicate a prevalent trend of coastal regression (Bourhili *et al.*, 2023; Aangri *et al.*, 2024; Lharti *et al.*, 2024; Naji *et al.*, 2025). However, this general trend is not uniform across the entire coastline. Conversely, other research has documented cases of progradation and stability in less disturbed sandy shores (El Mimouni *et al.*, 2014; Nmiss *et al.*, 2021b; 2022; 2025a). Accurate assessment of coastal behavior remains challenging due to the complex nature of sedimentary cells, where zones of erosion, stability, and accretion coexist within the same beach system. Thus, longitudinal monitoring is essential for understanding the mechanisms that govern beach dynamics and inform effective coastal management strategies.

The assessment of shoreline evolution for Agadir beach through photo-interpretation and Geographic Information Systems (GIS) (DSAS tool) currently represents one of the most effective means of capturing the evolutionary state of a beach at a given time. These tools facilitate the spatial analysis of data and enable the production of precise maps detailing coastal dynamics and evolution. They are particularly effective for analyzing beach dynamics, allowing for the identification of long-term trends, delineation of accretion and erosion zones, and calculation of various parameters and indices measuring shoreline evolution. In recent years, the use of Geographic Information Systems (GIS) and high-resolution satellite imagery has become increasingly common in monitoring beach dynamics (Pardo-Pascual *et al.*, 2012; Luijendijk *et al.*, 2018; Matin, N., 2021; Mbezi, J., 2024; Darwish, 2024; Oliveira & Barboza, 2024; Nmiss *et al.*, 2025b). GIS, with its capabilities to acquire, compile, store, manipulate, analyze, and display georeferenced data (Clarke, 1986; Nmiss *et al.*, 2019; 2020; Nait-Si *et al.*, 2022), provides tools well-suited for such environments, where multiple interacting components converge. This study aims to analyze the shoreline evolution trends of Agadir beach, located in the central-western part of Morocco. The selection of this site as a case study to investigate coastal dynamics over the past five decades (1968-2023) is justified by its high level of anthropogenic influence and its status as a major tourist destination, popular among both national and international visitors. The significance of this research lies in the use, for the first time, of high-resolution spatial data to study shoreline evolution. These data allow for a more accurate quantification of coastal dynamics by clearly identifying zones of erosion, accretion, and stability.

2. Study Area

On the Moroccan Atlantic coast, Agadir beach is located at the end of a bay, protected to the north by the Cap Ghir headland and opening widely towards the continent (Souss plain) to the east (Fig. 1b). It stretches for approximately 7 km between the Agadir port complex in the north (comprising the commercial port, fishing port, and marina) and the mouth of the Souss River in the south (Fig. 1c). This beach is highly anthropized (more than 500000 inhabitants according to the 2024 general population and housing census) and is one of the most popular tourist destinations for both national and international visitors (Faouzi, 2013). From a hydrodynamic perspective, according to the daily forecasts of the Spanish port authorities at point Simar 1040022, Agadir beach is exposed to swells and energetic waves from the NNW sector, with over 60% of waves having a significant height of less than 3 m and more than 50% of waves having a period exceeding 10 seconds (Aangri *et al.*, 2023, Nmiss *et al.*, 2025a). The tides in Agadir bay are semi-diurnal and mesotidal, with an average spring tide amplitude of 2.9 m and an average neap tide amplitude of 1.3 m (Aouiche, 2016). The Agadir region experiences a semi-arid to arid Mediterranean climate, heavily influenced by the Atlantic Ocean. It is characterized by hot summers and mild winters. Precipitation is irregular over time, with an average annual rate of 213 mm recorded at the Agadir station (Atiki *et al.*, 2019).

Coastal developments on Agadir beach began during the colonial period in 1917 with the construction of breakwaters, jetties, and the Agadir port basin (Tab. 1). Following the earthquake in 1960 that devastated the region, destroying the entire city and causing more than 60,000 deaths (Ennassiri & Mouak, 2021), a new master plan for the reconstruction of the Agadir area was implemented, which completely transformed the coastal landscape (Mansoum, 1994a). This transformation included significant expansion of built-up areas, the construction of breakwaters and a groyne to the south of the beach (1968-1993), and the construction of a new commercial port (1988) (Mansoum, 1994b; Mansoum, 1993). These developments were made at the expense of the coastal dune, which disappeared entirely due to the construction of hotel complexes and a promenade along the beach.

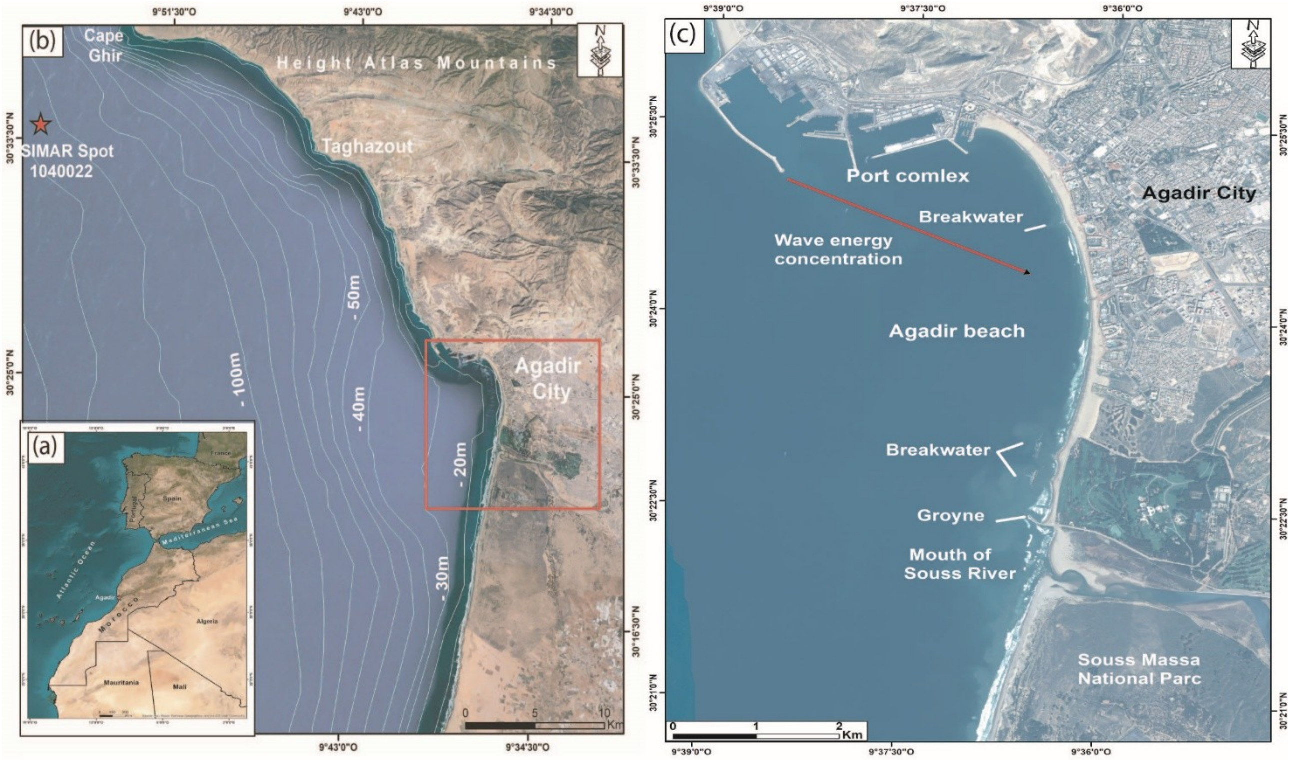

Figure 1. Location of the study area; (a) An overview of Agadir's location on the map of Morocco; (b) The location of the beach at the head of Agadir Bay, with isobaths representing the bathymetric levels of the continental shelf (https://www.navionics.com/fra/). The red star marks the SIMAR 1040022 point, extracted from the daily forecast of the Spanish Ports Authority (https://www.puertos.es/en/services/oceanography); (c) An aerial view of Agadir Beach showing the high level of anthropization and the various coastal developments.

Figura 1. Localização da área de estudo; (a) Uma visão geral da localização de Agadir no mapa de Marrocos; (b) A localização da praia na cabeceira da Baía de Agadir, com isóbatas representando os níveis batimétricos da plataforma continental (https://www.navionics.com/fra/). A estrela vermelha marca o ponto SIMAR 1040022, extraído da previsão diária da Autoridade Portuária Espanhola (https://www.puertos.es/en/services/oceanography); (c) Uma vista aérea da Praia de Agadir, mostrando o alto nível de antropização e os diversos empreendimentos costeiros.

Table 1. The main developments carried out in the Bay of Agadir (Source: Moroccan Directorate of Ports and Public Maritime Domain).

Tabela 1. Os principais empreendimentos realizados na Baía de Agadir (Fonte: Diretoria Marroquina de Portos e Domínio Público Marítimo).

Period	Main Human Interventions
1917-1920	Construction of the first dike of the port of Agadir with a length of 206 m
1940-1948	Extension of the jetty up to metric point 940 and construction of the fish market hall
1950-1953	Construction of a basin, protected by the southern dike with a total length of 1600 m
1960	Agadir earthquake; establishment of the new master plan for the city's reconstruction, which completely transformed the coastal landscape
1968	Installation of a 200 m breakwater south of the fishing port jetty to protect this area from erosion
1982-1988	Construction of the new commercial port: for this, 1.2 million m³ of sediments were dredged at depths from -10 m to -20 m off the Souss River, and 800,000 m³ near the entrance channel of the old port
1993	Construction of a defense system consisting of two breakwaters, each approximately 220 m in length, and a groyne aimed at combating erosion near the royal palace
1990-2005	Complete destruction of the coastal dune over a length of 7 km between the mouth of the Souss River and the port complex due to the construction of hotels

2. Materials and Methods

In this study, the diachronic analysis of shoreline change is based on high-resolution satellite images and orthophotos from multiple sensors (Corona, OrbView-3, Pléiades, WorldView) (Tab. 1). Although these datasets provide specific and momentary snapshots, comparative analysis can reveal distinct phases of geomorphological evolution along the shoreline (Nmiss *et al.*, 2019). Analysis and processing of these spatial data sources were conducted using digital image processing techniques. This approach follows the methodology proposed by Theiler & Danforth (1994), which includes georeferencing satellite images, correcting distortions and transformations, digitizing, and performing a diachronic overlay of successive shoreline positions (Fig. 2).

The georeferencing process used high-resolution orthophotos from the Pléiades satellite to minimize distortions and transformations that could otherwise skew the results of diachronic analysis. The high-tide line was selected as the shoreline position, as this line is distinctly visible in spatial data due to the color difference of the intertidal zone exposed at low tide (Crowell *et al.*, 1991; Moore, 2000; Robin, 2005). Despite the limitation due to the variability of tide, this high-tide line remains the most commonly used indicator for examining shoreline variability (Dolan *et al.*, 1991; Boak & Turner, 2005; Moore, 2006; Hanslow, 2007).

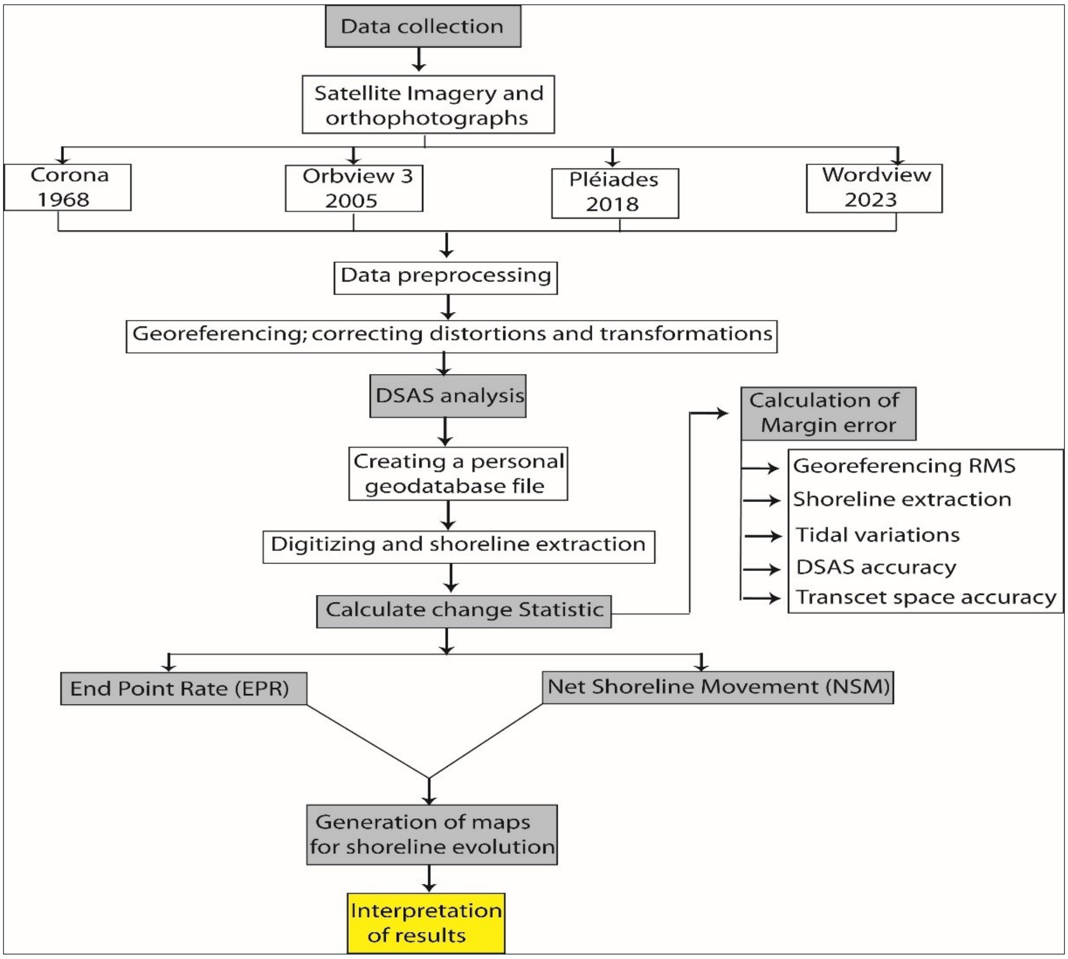

Figure 2. The main steps followed for the study of shoreline evolution.

Figura 2. As principais etapas seguidas para o estudo da evolução da linha de costa.

Table 2. The satellite images and orthophotographs used in the coastline extraction.

Tabela 2. As imagens de satélite e ortofotografias utilizadas na extração da linha de costa.

Spatial Data		Date of shoreline extraction	spatial resolution	Source
Satellite Imagery and orthophotographs	Corona	February 03, 1968	0.6 m	https://earthexplorer.usgs.gov/
	OrbView-3	November 21, 2005	1 m	https://earthexplorer.usgs.gov/
	Pléiades	October 29, 2018	0.5	https://visor.grafcan.es/agadir
	WordView	September 10, 2023	0.3	https://map.openaerialmap.org

3.1. Quantification of Shoreline Evolution

To quantify the evolution of the shoreline at Agadir beach across different temporal scales, we utilized the Digital Shoreline Analysis System (DSAS), an ArcGIS© add-in developed specifically to assess historical shoreline change rates by analyzing a series of shorelines from various dates (Theiler *et al.*, 1994; Oyedotun, 2014). DSAS enables users to calculate coastal change rate statistics across a chronological sequence of shoreline positions (Himmelstoss *et al.*, 2018). The DSAS tool is based primarily on generating transects along the coastline from a designated baseline, which is a reference line constructed inland. In this study, a total of 6,406 transects, spaced 1 meter apart from each other, were used. These transects intersect with the shorelines, allowing for the calculation of two primary parameters. The first is the Net Shoreline Movement (NSM), which measures the distance between the oldest and most recent shoreline positions for each transect. The second parameter is the End Point Rate (EPR), calculated by dividing the shoreline displacement distance between the earliest and latest measurements by the number of years, thereby providing an annualized rate of change.

3.2. Evaluation of the Margin of Error

Before quantifying shoreline evolution, it is essential to evaluate several uncertainties primarily related to the quality of spatial data on which the analyses rely, the georeferencing of the data, the extraction of the shoreline, default data uncertainly of DSAS Tool, and variations in the reference line position (high-tide line) (Appeaning Addo *et al.*, 2008; Sutherland, 2012; Jonah *et al.*, 2016). Within a diachronic analysis of shoreline change, these factors could skew results, making it crucial to assess these uncertainties before drawing conclusions on coastal kinematics (Thieler & Danforth, 1994; Durand, 2000; Robin, 2005).

The margin of error related to the quality of the data used in this study is 0.6 pixels, or 0.6 m. This low margin of error here is due to the high quality and spatial resolution of the data employed, which provides a very clear and precise view of the coastline. The error related to data georeferencing (RMS) is 1.7 pixels, or 1.7 m. As for the error associated with coastline extraction, it is estimated at 2.5 m. This value was determined after several repetitions of coastline digitization. For the error related to default data uncertainly of DSAS tool, the U.S Geological Survey (USGS) provides a suggested default value of 10 meters, which is the approximate average of uncertainty of various shoreline data types used in recent regional reports that the U.S. Geological Survey has published under the National Assessment of Shoreline Change project (Himmelstoss *et al.*, 2018).

For the error margin related to tidal variations (high tide-low tide). Stafford and Langfelder (1971) demonstrated that, to minimize effects related to high-tide line variation in comparative studies based on photo-interpretation and spatial imagery, images should be captured simultaneously and under similar tidal conditions. In this study, tidal conditions (high/low tide) for all image acquisitions were gathered from the Agadir port records (Fig. 3). These data are accessible via the website of France's hydrographic and oceanographic service (www.shom.fr), reveal significant variations, with high tide levels ranging from approximately 2.9 m on September 10, 2023, to 3.5 m on February 3, 1968, and tidal ranges varying from a minimum of about 1.4 m on November 21, 2005, to a maximum of approximately 2.2 m on February 3, 1968.

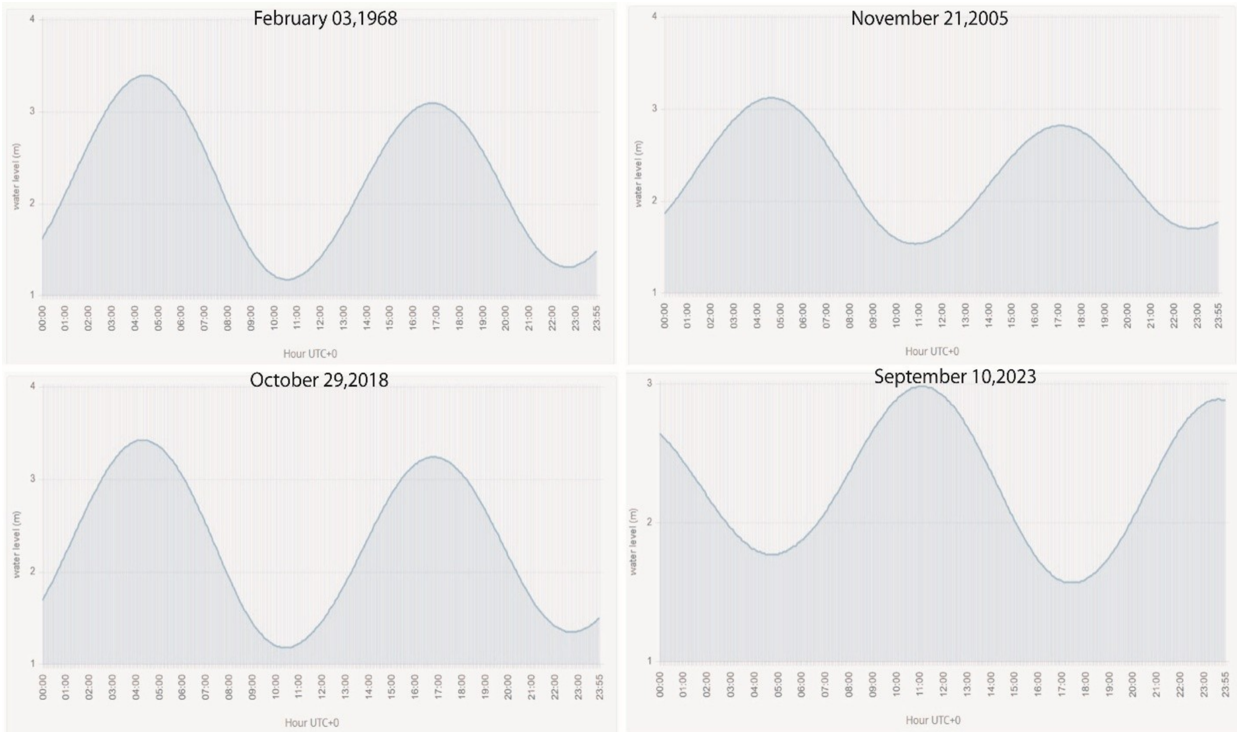

Figure 3. Tide gauge record showing the tidal state during the period when spatial data were collected (www.shom.fr).

Figura 3. Registro do mareógrafo mostrando o estado das marés durante o período em que os dados espaciais foram coletados (www.shom.fr).

Moreover, determining beach slope at the time of aerial and satellite image capture is crucial for calculating the margin of error. The slope of the beach was adopted from Aouiche *et al.* (2016a) is approximately 2°. Based on the beach slope (θ) and water height (h), it is possible to calculate the discrepancy between maximum and minimum high-tide levels (Δd) using the following formula (Thomas & Diaw, 1997): $\Delta d = h / \tan(\theta)$. The average discrepancy between maximum and minimum high tide is approximately 2 m. The margin of error related to tidal variations (Δd) is 58.86 m.

The total uncertainty (UT) is calculated as the square root of the sum of the individual uncertainties (Taylor, 1997). 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.

4. Results

The analysis of the shoreline evolution of Agadir beach over a 55-year period (1968-2023) reveals a marked dynamic, distinguishing two distinct sectors. The first sector is located at the bay's innermost area and extends 2.8 km south along the beach. This is an area of accretion and stability, with varying degrees of shoreline advancement depending on the location, with a maximum recorded at the bay's innermost point, near the marina. In this part of the beach, the maximum rate of shoreline advance is 223 m, or 4 m/year. This rate gradually decreases southward, reaching 11 m, or 0.2 m/year, near transect 2800 (Figs. 4 and 5). The second sector spans the remaining stretch of beach, extending to the mouth of the Oued Souss (Fig. 4). This is an area of erosion and shoreline retreat, with a maximum retreat rate of -107 m, or -1.94 m/year, recorded at the southern end of the beach, in front of the royal palace. The retreat rates vary significantly by area, ranging from -3.5 m to -92.7 m, which correspond to annual values of -0.06 m to -1.68 m. However, slight accretion has been noted at transects 5488 and 5019, primarily due to the breakwater installed in front of the royal palace in 1993 (Figs. 4 and 5).

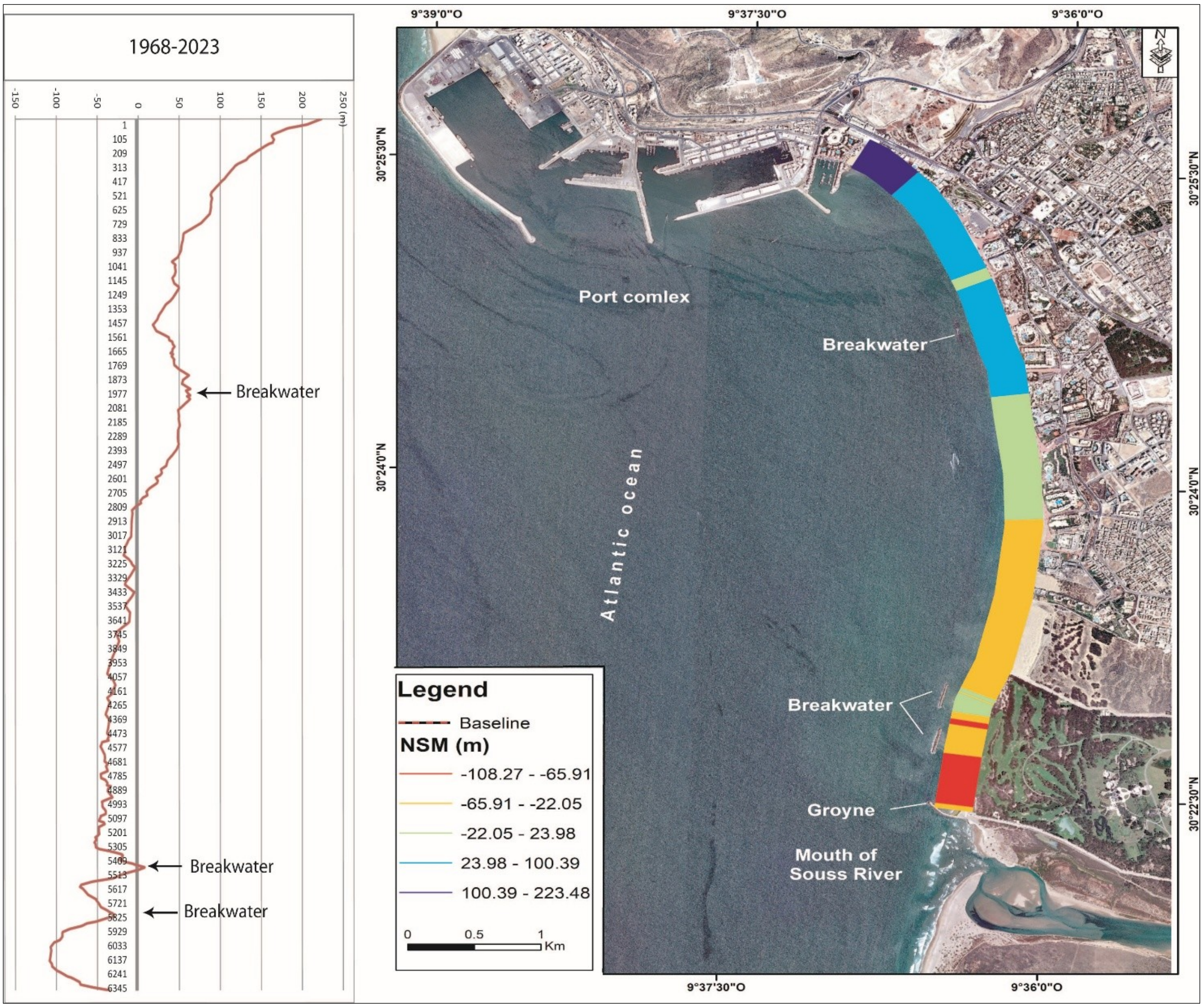

Figure 4. The overall evolution of the coastline between 1968 and 2023 from Net shoreline movement (NSM).

Figura 4. A evolução geral da linha de costa entre 1968 e 2023 com base no Movimento Líquido da Linha de Costa (Net Shoreline Movement - NSM).

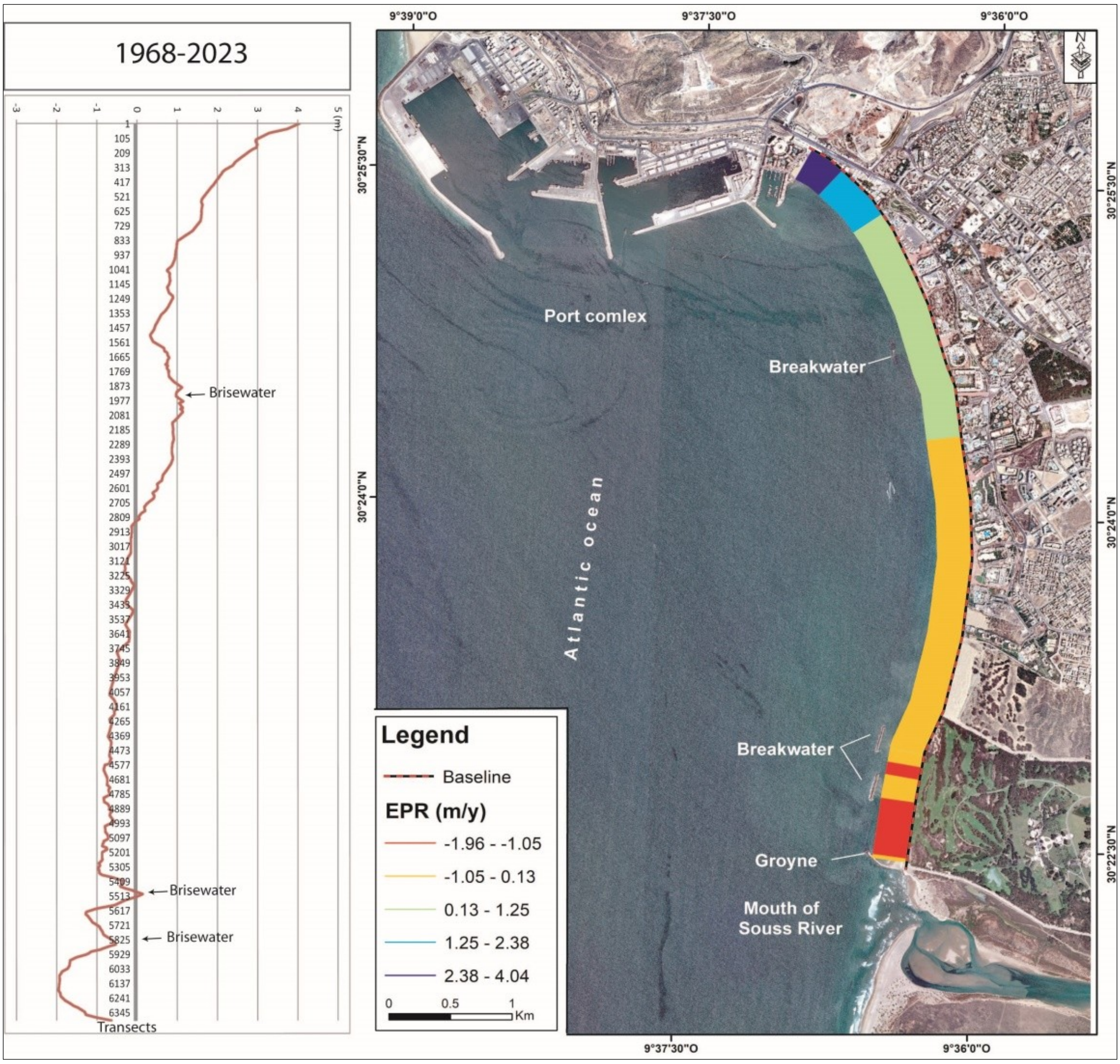

Figure 5. Annual Shoreline Evolution (End Point Rate) at Agadir Beach between 1968 and 2023.

Figura 5. Evolução Anual da Linha de Costa (Taxa de Ponto Final) na Praia de Agadir entre 1968 e 2023.

To evaluate the shoreline evolution across multiple temporal scales, three distinct time intervals were delineated: 1968–2005, 2005–2018, and 2018–2023. These intervals were selected to capture the dynamics of Agadir Beach's evolution at varying temporal resolutions, thereby enabling a more nuanced understanding of its morphodynamic behavior. The synthesized data, presented in Figure 6, facilitate a comparative analysis of these periods.

For the 1968–2005 interval, the observed trends align closely with the long-term evolution (1968–2023), characterized by pronounced accretion in the northernmost sector of the bay and persistent erosion in the central and southern segments of the beach (Fig. 6). In contrast, the analysis of shorter timeframes (2005–2018 and 2018–2023) reveals a discernible shift toward increased accretion and enhanced morphodynamic stability across the beach. Nevertheless, localized areas of erosion continue to persist, as detailed in Figure 7. This suggests that while the overall trend indicates shoreline stabilization, the underlying processes driving erosion remain active in specific zones, warranting further investigation into the contributing factors. This multi-temporal approach underscores the importance of considering both long-term and short-term dynamics in coastal studies, as it provides a more comprehensive understanding of the complex interplay between natural processes and anthropogenic influences on shoreline evolution.

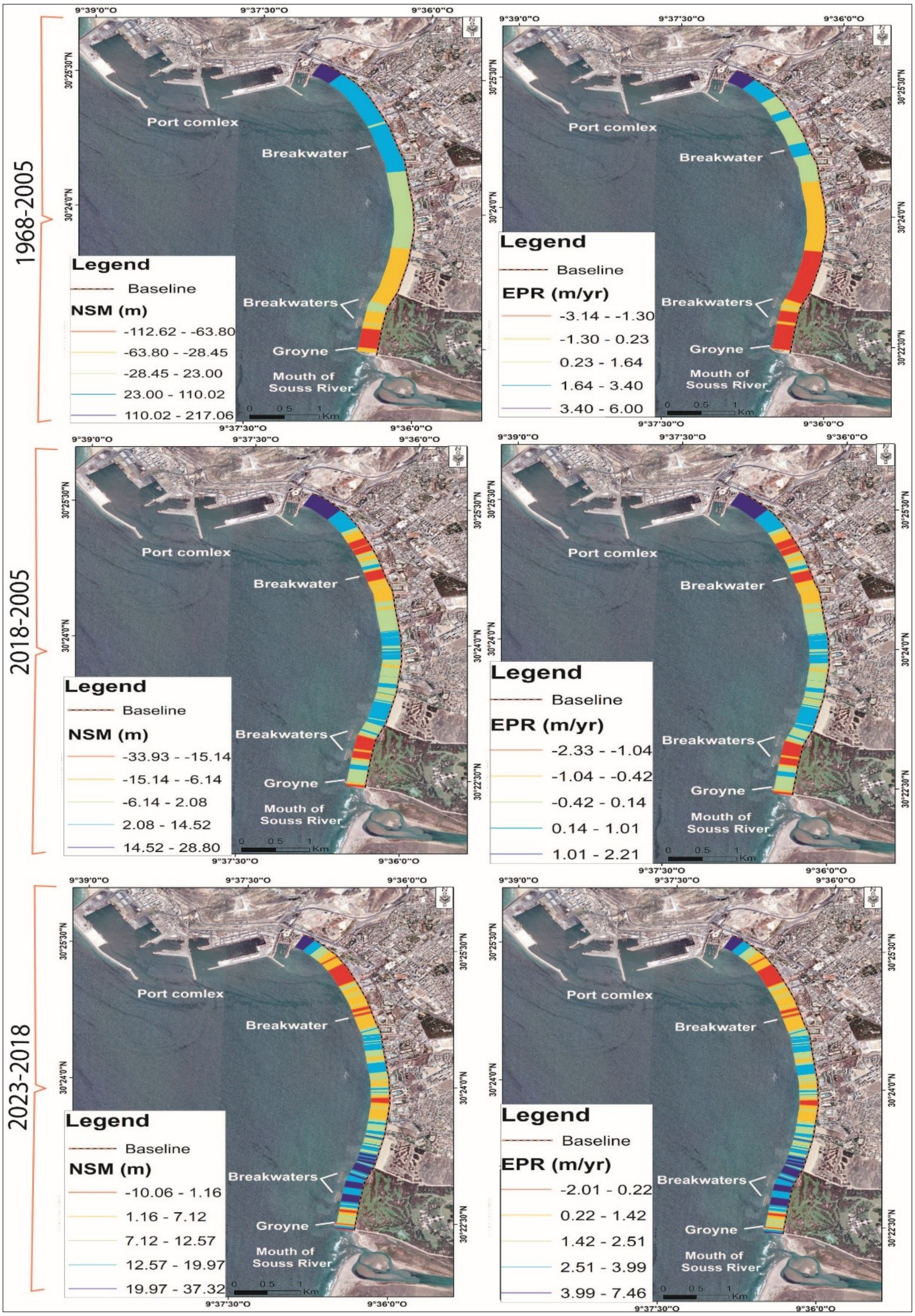

Figure 6. Net Shoreline Evolution (NSM) and End Point Rate of Agadir Beach at Different Dates (1968-2005) (2005-2018) (2018-2023).

Figura 6. Evolução Líquida da Linha de Costa (NSM) e Taxa de Ponto Final (EPR) da Praia de Agadir em Diferentes Datas (1968-2005) (2005-2018) (2018-2023).

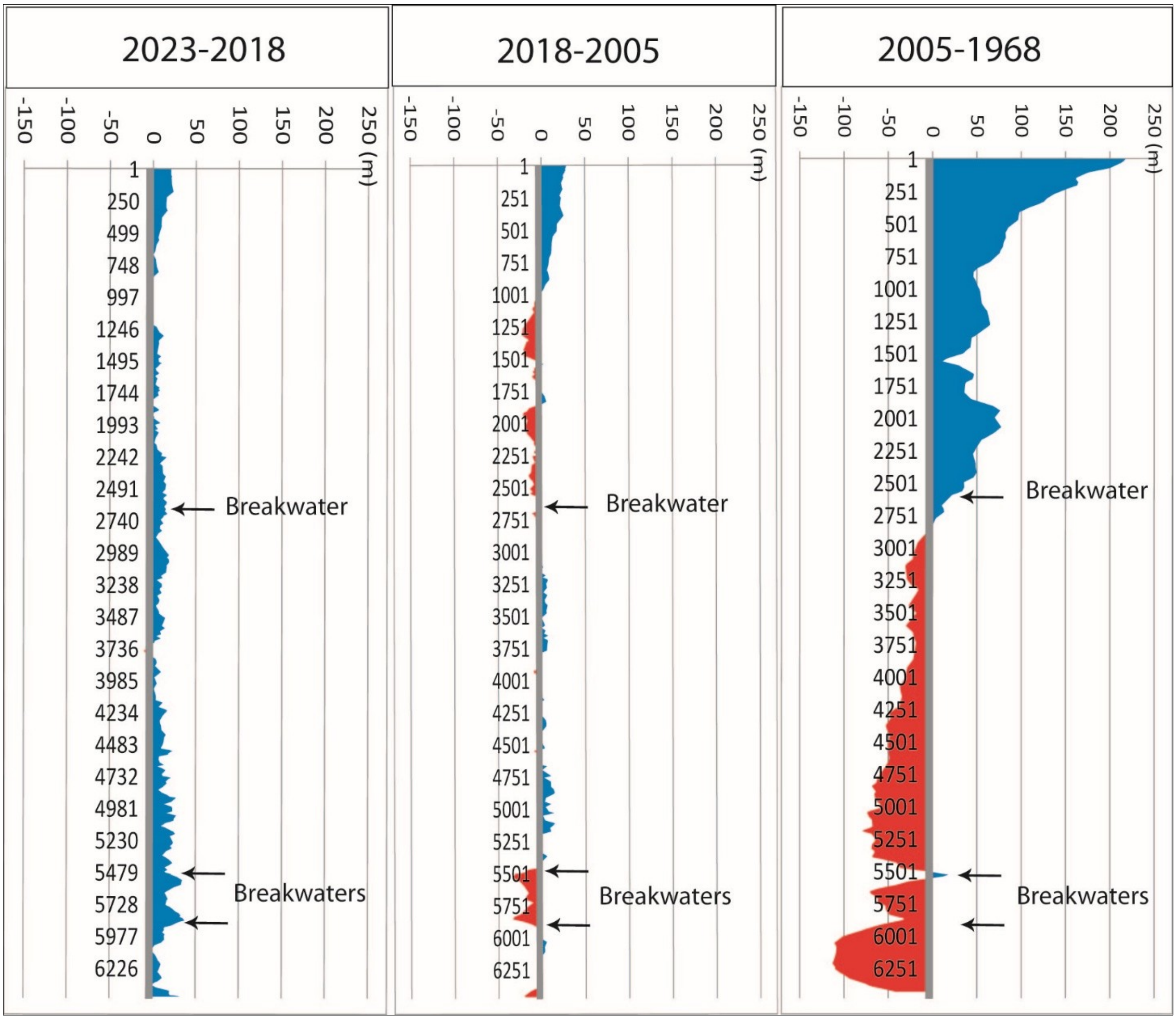

Figure 7. Net Shoreline Evolution (NSM) of Agadir Beach at Different Dates.

Figura 7. Evolução Líquida da Linha de Costa (NSM) da Praia de Agadir em Diferentes Datas.

4. Discussion

The study of the coastline evolution through high-resolution satellite imagery and the use of the DSAS tool allowed for the analysis and quantification of shoreline changes over a 55-year period, from 1963 to 2023. The results reveal a spatio-temporal variability in the evolution of Agadir Beach, with areas of accretion, areas of erosion, and areas in equilibrium. Over the long term (1968-2023), and during the period 1968-2005, the diachronic analysis of the coastline highlights two distinct sectors: a northern sector in accretion and a central and southern sector experiencing erosion and retreat.

This evolutionary trend is primarily explained by the establishment of a port complex to the north of the city of Agadir, including a commercial port, a fishing port, and a marina (Fig. 8). Over the long term, this complex has influenced the geomorphological evolution of the coastline, as evidenced by the sediment accretion patterns observed north of the beach in our results (see Fig. 4). These changes are likely due to the creation of a hydrodynamically calm zone, sheltered from prevailing wave action and energetic winter swells, caused by the port structures. The significant wave height in this part of the beach is around 0.7 m (Aouiche, 2016), thus favoring conditions conducive to accretion in the intertidal zone.

In contrast, areas highly exposed to erosion have developed in the central and southern sectors of the beach (Fig. 9). These areas are subjected to waves with significant heights of up to 2.8 m (Aouiche *et al.*, 2016), which, during the winter months, can rise to 5 meters during storms, as was the case with the storm of March 1, 2018, which severely impacted Agadir Beach (Nmiss *et al.*, 2021a). The effects of this storm are particularly evident in the central and southern parts of the beach (Fig. 9 (a) and (b)), where it caused a radical change in the coastal morphology, and recovery may take several years, or even decades, to return to its pre-storm configuration. More than two meters of accumulated sediment on the beach were eroded and carried offshore (Nmiss *et al.*, 2021a) (Fig. 9a).

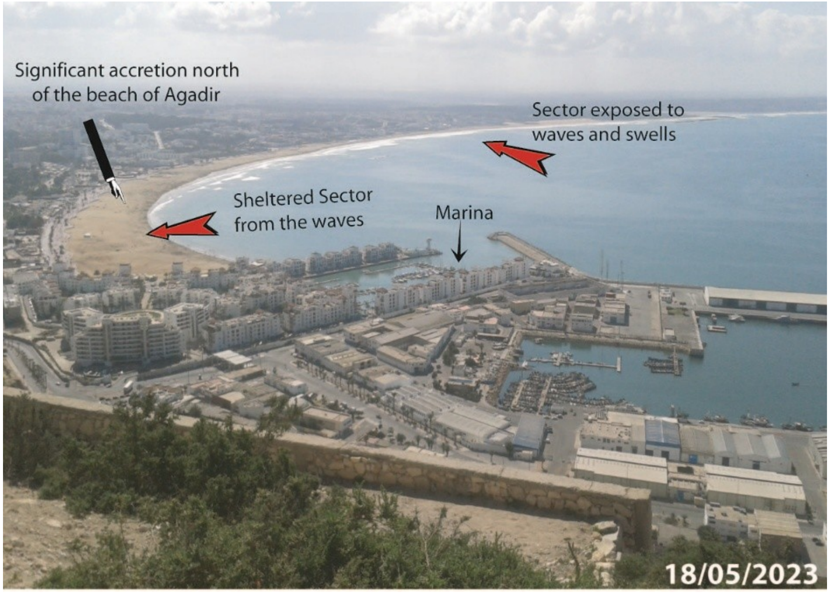

Figure 8. A panoramic photo of Agadir Beach illustrates the impact of the port complex in creating two sectors: one sheltered from the waves and the other exposed.

Figura 8. Uma foto panorâmica da Praia de Agadir ilustrando o impacto do complexo portuário na criação de dois setores: um protegido das ondas e outro exposto.

Figure 9. Significant erosion was observed in the central and southern sectors of Agadir Beach following the storm on March 1, 2018. Photos (a) and (b) show a large quantity of sand carried offshore by waves exceeding 5 meters, leaving behind a micro-cliff several meters high (a) and clear signs of marine erosion (b). (Source: personal photographs).

Figura 9. Erosão significativa foi observada nos setores central e sul da Praia de Agadir após a tempestade de 1º de março de 2018. As fotos (a) e (b) mostram uma grande quantidade de areia carregada para o mar por ondas que ultrapassaram 5 metros, deixando para trás uma micro-falésia com vários metros de altura (a) e sinais claros de erosão marinha (b). (Fonte: fotografias pessoais).

The complete disappearance of the coastal dune system, which occurred gradually between 1990 and 2005 due to the construction of hotel complexes and a beachfront promenade on the upper beach, is a major factor explaining the intense erosion observed in the central and southern sectors of Agadir Beach during that period. These dunes played a crucial role as natural regulators, buffering wave and current energy and acting as a sediment reservoir that could be mobilized by wind or coastal processes in response to dynamic conditions. Their removal significantly reduced the beach's capacity to maintain a natural balance between erosion and accretion.

On the beaches of Massa, located 30 km south of Agadir, the presence of a well-developed upper beach dune similarly provides a sediment reserve that can supply the beach in times of sediment deficit (Nmiss *et al.*, 2021b). Corona satellite images reveal that a complex of upper beach dunes, previously stabilized by vegetation cover, once extended along the entire Agadir Beach (Fig. 10a). However, since 2005, these dunes have completely disappeared, replaced by a promenade, which has led to beach consolidation and, consequently, an acceleration of marine erosion (Fig. 10 b). Moreover, the comparison between the 1968 Corona images and those from Google Earth Pro in 2023 reveals a significant change at the mouth of the Souss River (Fig. 10a and b). This change is due, on the one hand, to the installation of a coastal defense system (a groyne and two breakwaters) aimed at protecting the wall of the Royal Palace of Agadir, and on the other hand, to the reduction in the river flow of the Souss, resulting from the construction of several dams upstream in the Souss watershed (Nmiss *et al.*, 2025b).

Although a defensive system comprising three breakwaters and a groyne was constructed in 1993 to reduce erosion near the royal palace, its effects remain localized and insufficient to stabilize the wider beach system. The trend toward relative stability observed since 2005 may reflect a shift in sediment dynamics, possibly due to the remobilization of offshore sediment stocks or changes in wave energy and direction. Thus, while the removal of dunes contributed to earlier phases of erosion, more recent stabilization may result from evolving sediment pathways and hydrodynamic conditions.

In this context, Agadir Beach would benefit from a more comprehensive and sustainable coastal defense strategy. While increasing the number of breakwaters in the central and southern sectors could help mitigate the effects of marine erosion, it is equally important to explore more sustainable and nature-based solutions. For instance, the restoration and stabilization of dune fields, along with beach nourishment, could serve as effective, environmentally friendly measures to enhance coastal resilience in the face of sea-level rise and climate change.

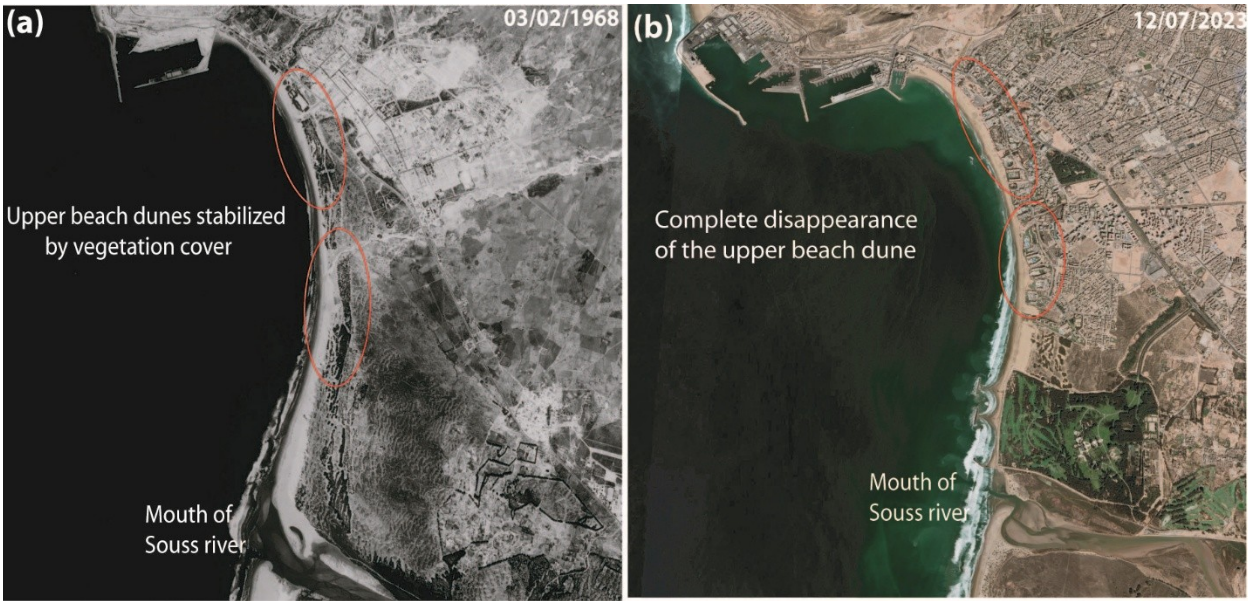

Figure 10. Two satellite images show the complete disappearance of the upper beach dune following various tourist developments on the beach.

Figura 10. Duas imagens de satélite mostram o desaparecimento completo da duna da praia superior após diversos empreendimentos turísticos na praia.

At a smaller scale (2005–2018 and 2018–2023), the evolutionary trends of Agadir Beach indicate accretion and relative stability. This trend may be attributed to the presence of a significant sediment stock in the nearshore area. An analysis of isobath distribution on the continental shelf (Fig. 1b) reveals the presence of a sediment cone off the Souss River mouth, which pushes the -50 m isobath approximately 15 km offshore. Although this sediment stock is not recent, we hypothesize that shifts in wave dynamics or changes in coastal sediment transport patterns—potentially induced by infrastructure development or climatic variations — may have enhanced sediment remobilization and its availability for beach accretion since 2005. This could explain the observed accretion and relative stability of Agadir Beach over the recent periods (2005–2018 and 2018–2023).

At this depth, shell sands and coastal sands are predominant (Mattieu, 1970). The calcium carbonate ($CaCO_3$) content in this part of the beach ranges from 20% to 65%, values similar to those obtained by Aouiche *et al.* (2016 b) in the intertidal zone of Agadir Beach, confirming that the existing sediment stock in the nearshore zone is a potential sand source. This stock could supply the beach in the event of total dune disappearance and reduced river flow. This hypothesis has been extensively discussed for mid- to high-latitude beaches (Laugier *et al.*, 2019; Anthony & Aagaard, 2020; Nmiss *et al.*, 2022; 2024; 2025a), showing that carbonate-rich continental shelf sediments could serve as a sediment source for beaches and dunes in the years to come. This hypothesis has also been proposed for other Moroccan beaches facing similar sediment deficits. On Saïdia Beach (Bouabdallah & Larue, 2009), located in the northeastern Mediterranean zone, offshore carbonate-rich deposits were identified as potential sediment sources, particularly after the disruption of dune systems and reduced river inputs. Similarly, on El Jadida Beach, near the Oum Rbia mouth, studies by Khouaja *et al.* (2016) suggest that offshore sediment stocks could contribute to beach stability following the construction of protective jetties and the disappearance of natural dune buffers. In the hyper-arid coastal system between Boujdour and Cap Blanc, Nait Hammou *et al.* (2025) have also demonstrated that shelf sediment reservoirs play a key role in maintaining beach sediment balance without fluvial input, particularly during winter storms. These examples reinforce the relevance of considering the nearshore sediment stock of Agadir Beach as a plausible and active source in recent shoreline stability trends.

5. Conclusions

The study of the shoreline evolution of Agadir Beach, based on high-resolution satellite imagery and NSM and EPR parameters, has enabled the quantification of shoreline advance and retreat rates at various spatial and temporal scales. The findings reveal two distinct evolutionary trends. On the one hand, the long-term evolution (1968–2023 and 1968–2005) indicates two clearly defined sectors: an accreting area in the northern part of the bay and an eroding area in the central and southern sectors. On the other hand, the medium-term evolution (2005–2018 and 2018–2023) is characterized by a general trend toward accretion and stability, although some erosion areas persist. Several factors contribute to these evolutionary dynamics of Agadir Beach. Firstly, port development, notably the construction of a coastal port complex north of Agadir, has significantly altered the beach's natural dynamics by creating a calm hydrodynamic area in the north, while the central and southern sectors remain highly exposed to wave action. Secondly, the complete disappearance of the coastal dune, resulting from the construction of a hotel complex and the beachfront promenade, played a significant role in the erosion processes observed during the earlier periods, particularly between 1968 and 2005. These infrastructures disrupted the natural sediment buffer and reduced the beach's capacity to resist marine erosion. However, the trend toward stability observed in the more recent periods (2005–2023) may be attributed to a shift in sediment dynamics, likely due to the remobilization of offshore sediment stocks. This recent accretion does not negate the impacts of dune removal but rather suggests a complex interplay of factors that temporarily offset those effects. Finally, the presence of a sediment stock, currently reworked by waves and winter storms, could become a potential sand source for Agadir Beach in the coming years, especially as the disappearance of the coastal dunes and reduced river flow, due to the construction of multiple dams on the regional rivers, limit natural sediment inputs.

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