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Thirty-year evolution of the Atlantic coastline using the digital shoreline analysis system: A case study in Tangier, northern Morocco

Ali Hadek [1], Miriam Wahbi [1], Mohammed Hlal [2], Mustapha Maatouk [1], Omar El Kharki [1], Hakim Boulaassal [1], Otman Yazid-Alaoui [1]

[1] Laboratory for Research and Development in Applied Geosciences FSTT Abdelmalek Essaâdi University, Route de l'Aéroport, Km 10, Ziaten, BP: 416, 90000 Tangier, Morocco.
(AH) (Corresponding author) E-mail: ali.hadek@etu.uae.ac.ma ORCID iD: https://orcid.org/0009-0004-7278-1632
(MW) E-mail: mwahbi@uae.ac.ma ORCID iD: https://orcid.org/0000-0002-1911-2593
(MM) E-mail: mmaatouk@uae.ac.ma ORCID iD: https://orcid.org/0000-0003-3125-9149
(OEK) E-mail: elkharki@gmail.com ORCID iD: https://orcid.org/0000-0002-5023-9613
(HB) E-mail: h.boulaassal@uae.ac.ma ORCID iD: https://orcid.org/0000-0003-2342-4431
(OY-A) E-mail: o.yalaoui@uae.ac.ma ORCID iD: https://orcid.org/0000-0002-7100-2391
[2] Centre of Urban Systems (CUS), University Mohammed VI Polytechnic (UM6P), Lot 660, Ben Guerir 43150, Morocco.
(MH) E-mail: Mohammed.HLAL@um6p.ma ORCID iD: https://orcid.org/0000-0001-7059-5386

Summary: Tangier's northern Atlantic coastal zone, particularly from Achakar to Sidi Kacem, is under increasing pressure from urbanization and tourism, which exacerbates its vulnerability to coastal erosion. This study aimed to assess spatio-temporal changes, quantify erosion and accretion rates, and identify factors influencing the coastline's stability or retreat. Potential impacts of this erosion include the loss of coastal habitats and threats to local biodiversity. The methodology combined automatic shoreline extraction using multi-temporal Landsat images (1973–2024) and field-based DGPS surveys. The results show that the coastline is eroding at an average rate of –2.24 m year^{-1}, with erosion rates increasing in severity towards the south. Two beaches, Sidi Kacem and Houara, were studied in detail. Between 1973 and 1990, significant erosion occurred: –6.63 m year^{-1} at Sidi Kacem and –8.01 m year^{-1} at Houara. Between 1990 and 2015, erosion (–2.12 m year^{-1} at Houara) and accretion (+2.24 m year^{-1} at Sidi Kacem) fluctuated. From 2015 to 2024, alternating dynamics with reduced intensity were observed. While this erosion poses limited immediate threats to critical infrastructure such as the airport and road networks, the study highlights limitations, including satellite image resolution and temporal data gaps. Future research should integrate higher-resolution data (e.g. LIDAR) and evaluate anthropogenic impacts on coastal dynamics, including urban runoff, sand extraction and tourism infrastructure development, to improve management strategies in the Achakar–Sidi Kacem area.

Keywords: coastal erosion; shoreline dynamics; spatial analysis; Landsat imagery; DSAS; DGPS; anthropogenic impacts; Tangier coastline.

Evolución de treinta años de la costa atlántica utilizando el Sistema de Análisis Digital del Litoral: estudio de caso en Tánger, norte de Marruecos

Resumen: La zona costera atlántica septentrional de Tánger, en particular desde Achakar hasta Sidi Kacem, está sometida a una presión creciente debido a la urbanización y el turismo, lo que exacerba su vulnerabilidad a la erosión costera. Este estudio tiene como objetivo evaluar los cambios espacio-temporales, cuantificar las tasas de erosión y acreción, e identificar los factores que influyen en la estabilidad o retroceso del litoral. Entre los impactos potenciales de esta erosión se incluyen la pérdida de hábitats costeros y amenazas a la biodiversidad local. La metodología combina la extracción automática de líneas de costa mediante imágenes Landsat multitemporales (1973–2024) y mediciones DGPS en campo. Los resultados indican que la costa se erosiona a una tasa promedio de –2,24 m año^{-1}, con una intensidad creciente hacia el sur. Dos playas, Sidi Kacem y Houara, fueron analizadas en detalle. Entre 1973 y 1990, se registró una erosión significativa: –6,63 m año^{-1} en Sidi Kacem y –8,01 m año^{-1} en Houara. Entre 1990 y 2015, se observaron fluctuaciones entre erosión (–2,12 m año^{-1} en Houara) y acreción (+2,24 m año^{-1} en Sidi Kacem). De 2015 a 2024, se detectaron dinámicas alternantes de menor intensidad. Aunque esta erosión representa una amenaza inmediata limitada para infraestructuras críticas como el aeropuerto y las redes viales, el estudio revela limitaciones, como la resolución de las imágenes satelitales y vacíos temporales en los datos. Futuras investigaciones deberían integrar datos de alta resolución (ej. LIDAR) y evaluar los impactos antrópicos en la dinámica costera, incluyendo escorrentías urbanas, extracción de arena y desarrollo de infraestructuras turísticas, para mejorar las estrategias de gestión en el área Achakar–Sidi Kacem.

Palabras clave: erosión costera; dinámica litoral; análisis espacial; imágenes Landsat; DSAS (Sistema de Análisis Digital de Líneas de Costa); mediciones DGPS; impactos antrópicos; litoral de Tánger.

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INTRODUCTION

Coastal areas, where land meets the sea, play a critical role in sustaining biodiversity, supporting economies and providing cultural heritage (Celata and Gioia 2024). These dynamic regions are increasingly vulnerable to natural processes such as coastal erosion (Celata and Gioia 2024) and anthropogenic pressures such as urban development and infrastructure expansion (Intergovernmental Panel on Climate Change 2023). Coastal erosion, driven by waves, tides and currents, is often exacerbated by human activities that alter natural coastal defences (Bird 2008). Additionally, sea-level rise, commonly called coastal flooding, leads to sea-level rise–induced flooding, further accelerating shoreline loss (Church et al. 2013). This erosion and flooding reduce landmass and jeopardize coastal ecosystems (Vousdoukas et al. 2020), human settlements and key economic sectors such as tourism and fisheries (Barbier et al. 2011).

The assessment and management of these risks require a deep understanding of coastal dynamics (Mentaschi et al. 2018) and the movement of sediments and water along shorelines. The use of advanced tools such as the Digital Shoreline Analysis System (DSAS) has become increasingly important in this context (Isha and Adib 2020). The DSAS leverages remote sensing data to track shoreline changes and provide key indicators of coastal evolution, offering insights into both natural patterns and the impact of human interventions. The application of the DSAS to monitoring coastal zones enables more effective management and risk mitigation strategies (Nerves et al. 2024). particularly in areas experiencing significant changes due to climate change and anthropogenic pressures (Luijendijk et al. 2018).

The northern coast of Tangier, Morocco, a region of ecological significance and economic vitality, faces unprecedented threats from coastal erosion intensified by anthropogenic activities and climate stressors. This study evaluates the efficacy of the DSAS in deciphering shoreline dynamics and guiding risk mitigation strategies for this vulnerable coastline. By addressing gaps in data-driven coastal management, our study provides actionable insights for stakeholders balancing development and conservation.

In this context, we formulated the following hypotheses:

– The DSAS exhibits limitations in low-data-resolution environments, affecting erosion rate accuracy.
– Human interventions (e.g. port expansions and tourism infrastructure) directly amplify erosion rates in Tangier.
– High-resolution satellite data significantly enhance the precision of the DSAS in modelling sediment loss.
– DSAS-derived metrics can optimize coastal zoning policies to reduce socio-economic risks.

Coastal erosion, a globally documented phenomenon, results from the interplay of natural processes and human activities (Bezerra et al. 2007). In Tangier, rapid urbanization exemplified by the Tanger Med port expansion has disrupted sediment dynamics, exacerbating shoreline retreat (Oueslati 2017) While the DSAS has emerged as a critical tool for quantifying erosion rates through transect-based analysis (Nugawela et al. 2023), its reliance on historical data quality remains a persistent challenge, particularly in regions with fragmented monitoring systems.

Recent advancements in remote sensing, such as Sentinel-2 imagery (10 m resolution), offer opportunities to refine DSAS outputs. However, the system's inability to differentiate between cyclical natural variability and irreversible anthropogenic impacts limits its predictive power in rapidly developing areas such as northern Tangier (Bezerra et al. 2007).

Sea-level rise, a consequence of global warming, has emerged as one of the most critical factors contributing to shoreline loss and coastal flooding (Tran and Lakshmi 2024). The Intergovernmental Panel on Climate Change has projected that global sea levels could rise by up to 1 m by the end of the century, with profound implications for coastal regions worldwide (McInnes 2024). The impact of sea-level rise is especially severe in low-lying coastal areas, where even a small increase in sea levels can lead to significant inundation and land loss (Roberts 2024).

While natural processes dominate the shaping of the coastline (Tierolf et al. 2024), human activities have increasingly altered coastal dynamics. Urbanization, tourism and industrial development have led to the construction of seawalls, breakwaters and other forms of coastal armouring that disrupt the natural flow of sediments along the shore.

This interruption in sediment transport often leads to the erosion of adjacent unprotected areas, creating a cycle of degradation that extends along the coast. Moreover, land reclamation projects, especially in densely populated coastal regions, have significantly reduced the availability of natural buffers against coastal hazards such as wetlands and mangroves (Spalding et al. 2014), further exposing coastal zones to the impacts of erosion and flooding (Xiang et al. 2024).

Several studies have highlighted the paradox of human interventions to protect coastal areas (Naji et al. 2025). While such interventions may provide short-term protection for specific sites, they often lead to unintended consequences, including increased erosion and habitat destruction in other areas (Nordstrom 2014). This has led to growing calls for more sustainable approaches to coastal management that prioritize the restoration of natural systems and the use of adaptive, flexible solutions (Hinkel et al. 2018).

Monitoring coastal changes is critical for understanding the long-term evolution of shorelines and informing effective coastal management strategies. The DSAS has become one of the most widely used tools for tracking and analysing coastal dynamics. Developed by the United States Geological Survey (USGS), the DSAS allows researchers to measure shoreline changes over time using a range of spatial data (Angnuureng et al. 2023), including satellite imagery, aerial photographs and geographic information systems data.

The DSAS is particularly valuable for its ability to compute statistical metrics related to shoreline change such as the rate of shoreline movement, the distance of shoreline displacement, and the frequency of erosional and depositional events. These metrics provide essential insights into the drivers of coastal change, helping researchers and policymakers to identify high-risk areas and evaluate the effectiveness of management strategies. Recent studies have applied the DSAS to assess the impacts of climate change and human activities on coastal systems. For example, (Fajri et al. 2024) used the DSAS to track the retreat of coastal barriers in response to sea-level rise along the Agadir Bay of Morocco, finding that human interventions such as the construction of groynes and jetties have significantly altered sediment transport patterns. Similarly, a study by (Hlal et al. 2024) on the Saidia-Nador coastline used the DSAS to evaluate the long-term effects of erosion risk on the coastline and damage to nearby urban areas, highlighting the economic impact and infrastructure damage due to coastal retreat (Hadek et al. 2024).

Unlike the Tangier coast, where Atlantic currents mitigate erosion, the Saidia-Nador region exhibits higher vulnerability, with studies highlighting more pronounced coastal retreats due to urban expansion and infrastructure development (Hlal et al. 2024). A key distinction between Tangier and Saidia-Nador lies in their hydrodynamic conditions and sediment dynamics. Tangier's erosion rates are partly moderated by sediment transport facilitated by northern Atlantic currents. Conversely, the Nador-Saidia coast experiences limited sediment supply exacerbated by dam construction, leading to accelerated erosion rates.

The use of the DSAS and geographic information systems (especially ArcGIS) in coastal management has sparked debates among researchers and practitioners. Some argue that while these tools provide valuable data for understanding coastal changes, they may not fully capture the complexity of interactions between natural processes and human activities (Angnuureng et al. 2022) . Others contend that relying on historical data to predict future shoreline changes can lead to inaccurate forecasts, especially in regions where human interventions constantly alter the coastal landscape (Hinkel et al. 2019).

Debates also persist over the effectiveness of coastal management practices. Hard engineering solutions such as seawalls and breakwaters continue to be widely used, despite growing evidence that they exacerbate coastal erosion and habitat loss (Pontee 2013) Conversely, proponents of soft engineering approaches such as beach nourishment and dune restoration argue that these methods offer more sustainable long-term solutions by working with natural processes. The challenge lies in balancing these competing approaches while considering the social, economic and environmental implications of interventions (Xiang et al. 2024).

MATERIALS AND METHODS

Study area

The coastal region of Tangier Bay (Fig. 1), located at 35.7596°N 5.8330°W, is characterized by a complex interplay of geomorphological, climatic and hydrodynamic factors. Three primary geomorphological units define the area (Mamouni et al. 2019). To the west lies the sandstone massif of Jbel El Kebir, rising to elevations of 200 m, while the gently undulating Fahs plain dominates the central zone at approximately 100 m. To the east, the Anjera massifs complete this tripartite structure, forming a landscape of varied relief.

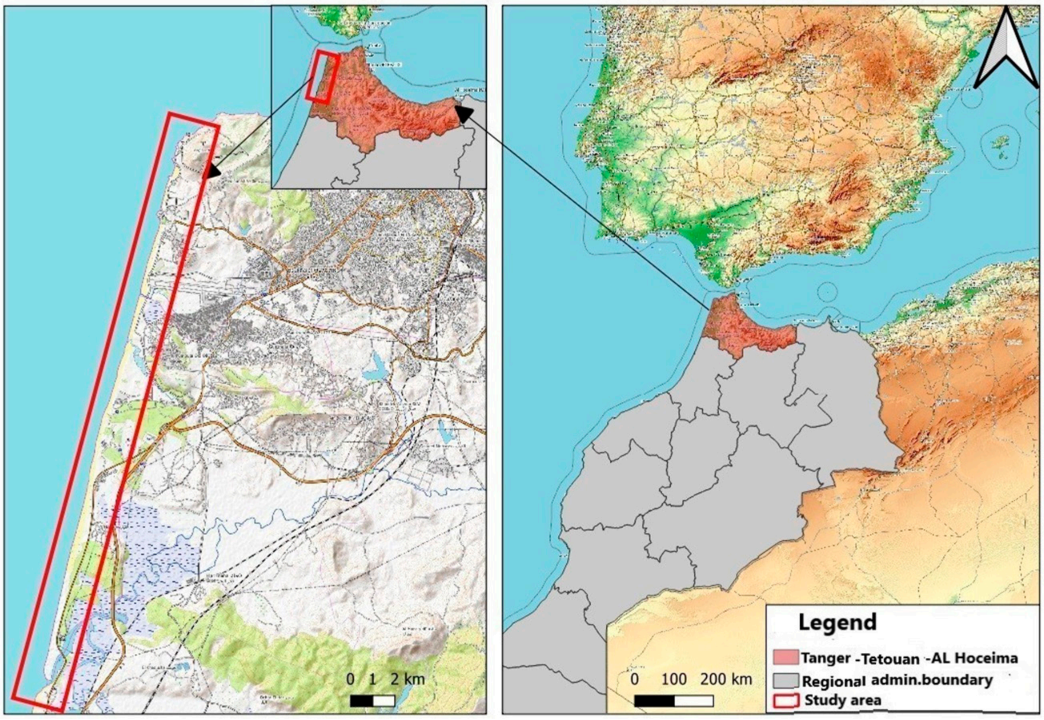

Fig. 1. – Study area.

The shoreline spans 25 km, featuring sandy beaches, coastal dunes and marshes, with a gentle slope of 0.8% to 1% (Lionello et al. 2006, El Talibi et al. 2016). However, the northern section contrasts sharply, being marked by rocky outcrops and cliffs composed of semi-consolidated marine or dune sandstones. These formations, reaching 30–50 m in height, are particularly prominent during storm events, underscoring the dynamic interaction between terrestrial and marine processes.

Climatically, the area experiences a Mediterranean sub-humid regime, with wet, mild winters and hot, dry summers (Lionello et al. 2006). The region is characterized by irregular and often torrential rainfall, predominantly concentrated during the winter months (December to February). On average, the area experiences approximately 66 rainy days per year. Conversely, the dry season coincides with the hot summer months (July and August), when precipitation is minimal.

Wind patterns play a pivotal role: the dry Chergui winds from the east and northeast dominate spring and summer, while the humid Gharbi winds from the west and northwest prevail in autumn and winter, driving precipitation. Wind activity is intense, with monthly speeds exceeding 18 km h^{-1} over 60% of the time, and calm conditions (<72 km h^{-1}) occurring less than 20% of the time.

Hydrodynamically, the region is governed by Atlantic swells and local wind-generated waves. Swells from the west to northwest, with periods of 7–18 seconds and amplitudes reaching 7–9 m, dominate the continental shelf. These contrast sharply with shorter-period (3–5 s), lower-height (<1.5 m) swells from easterly directions, generated by local winds. The dominant W–NW swells drive a south-to-southwest coastal sediment drift, while easterly swells induce lateral sediment transfer from east to west, particularly east of the bay, with wave incidences of 20°C to 30°C. Coastal currents, flowing north-to-south at 10–50 cm/s, further modulate sediment transport, though their patterns are influenced by seasonal variability and local geomorphology (Masselink and Russell 2013). Tidal dynamics are semi-diurnal, with an average amplitude of 1.8–2 m. Flood tides move eastward, while ebb tides reverse westward, contributing to the redistribution of sediments.

This tidal regime, combined with wave action, sustains a dynamic sedimentary environment. Recent studies highlight the bay's diverse sedimentary settings, shaped by a range of hydrodynamic conditions and processes (Abdellaoui 2007) Sandy beaches and dunes coexist with marshes and rocky substrates, reflecting the interplay of high-energy Atlantic swells, localized wind-driven waves and tidal currents.

Data and methods

This study relied on satellite imagery (Table 1), selected for a homogeneous period based on criteria of minimal cloud cover and radiometric consistency (Pardo-Pascual et al. 2018). Systematic preprocessing was performed using remote sensing software, including atmospheric correction (conversion to surface and Top-of-Atmosphere reflectance) and panchromatic band resolution enhancement to 5 m (Roy et al. 2014).

Table 1. – Satellite data used in morphodynamics analysis between 1973 and 2024.

Data Type	Description	Source	Temporal coverage	Spatial coverage	Resolution
Satellite Imagery	Multispectral imagery for land cover and coastal change detection.	Sentinel-2 (ESA), Landsat L1-L5-L7-L8-L9 (ESA), Modis (NASA)	1973–present	Coastal areas of Morocco	10 m (Sentinel-2), 250 m (MODIS), (30-60 m) Landsat.
Shoreline data	Historical shoreline positions used for erosion rate calculations.	DSAS (Digital Shoreline Analysis System)	1990–2023	Moroccan coastal zones	N/A
Topographic data	Elevation data used to assess coastal vulnerability and terrain changes.	SRTM (NASA), ASTER GDEM (METI/NASA)	2000–2020	Morocco	30 m (SRTM), 15 m (ASTER).
Meteorological data	Wind speed, wave height and sea-level data to assess factors influencing erosion.	Moroccan Meteorological Agency (Météo Maroc), ERA5 (ECMWF)	1980–present	Moroccan coast	Hourly, daily, monthly.
Bathymetric data	Seafloor topography and depth information for coastal morphology analysis.	Moroccan Hydrographic Service	2010–2020	Moroccan coastal waters	Change
Tidal data	Tide gauge data for monitoring sea-level changes and their impact on erosion.	Moroccan Ports Agency (ANP)	1980–present	Key Moroccan port locations	Hourly

Multi-temporal Landsat imagery was used to derive spectral indices (the NDVI, NDWI and AWEI) for water body analysis (Fig. 2). Among these, the NDVI (normalized difference vegetation index) and the AWEI (automated water extraction index) provided supplementary data, but the NDWI (normalized difference water index) was prioritized for shoreline extraction due to its enhanced sensitivity to land–water boundaries. To ensure accuracy, radiometric corrections were first applied to address geometric distortions caused by satellite positioning, Earth's rotation and topographic variations.

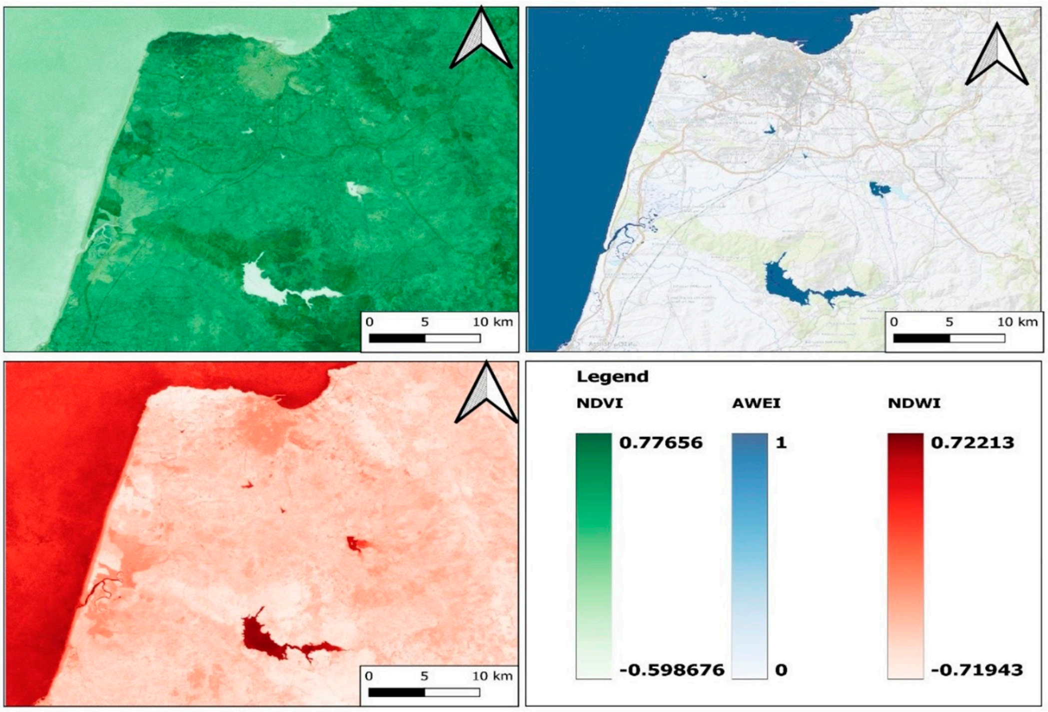

Fig. 2. – Spectral index map for the year 2024. NDVI, normalized difference vegetation index; AWEI, automated water extraction index; NDWI, normalized difference water index.

NDWI thresholds were calibrated using histogram analysis and visual interpretation (Pardo-Pascual et al. 2018). Water bodies were classified and NDWI values were generated via the Raster Color Slices tool. Extracted shorelines were overlaid onto NDWI outputs to validate spatial alignment (Fig. 3), with manual refinements ensuring temporal consistency and accuracy in the final time-series maps. Threshold calibration was further validated against high-resolution Google Earth imagery (0.5 m), following the methodological framework of (McFeeters 1996), to ensure robustness across spectral variability.

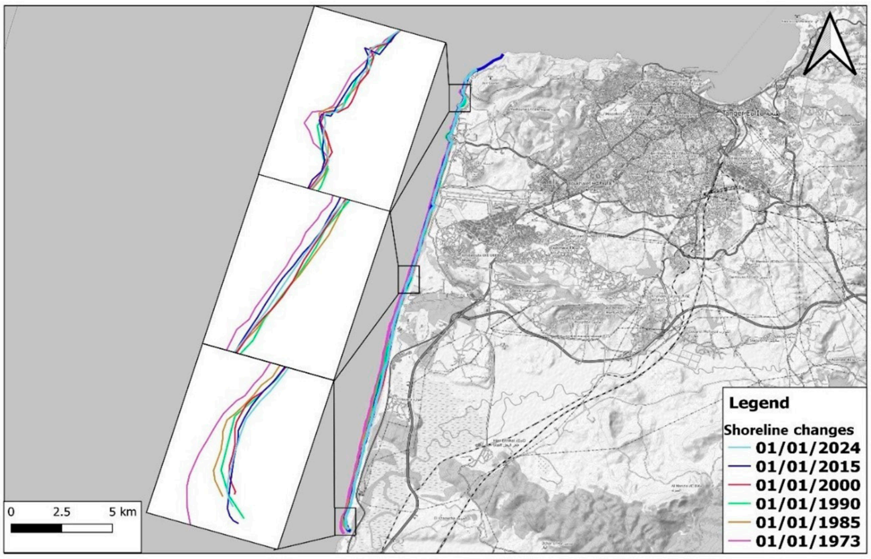

Fig. 3. – Multi-temporal shoreline evolution (1973–2024).

Shoreline dynamics were quantified using the DSAS. Baselines and transects were organized within a geodatabase. We employed the transect-based method integrated within the DSAS to assess coastline evolution. This approach involves constructing transects that are perpendicular to a user-defined reference baseline and intersect shorelines from multiple periods (Xu 2008).

Transects are only generated when a consistent and approximately parallel alignment between the baseline and the historical shorelines is ensured (Quang et al. 2021). Once attributes had been assigned to both the shorelines and the baseline, the DSAS was used to generate transects (Fig. 4). The intersections of these transects with the shoreline vectors provide precise measurement points, capturing both spatial and temporal information and allowing shoreline change metrics to be calculated.

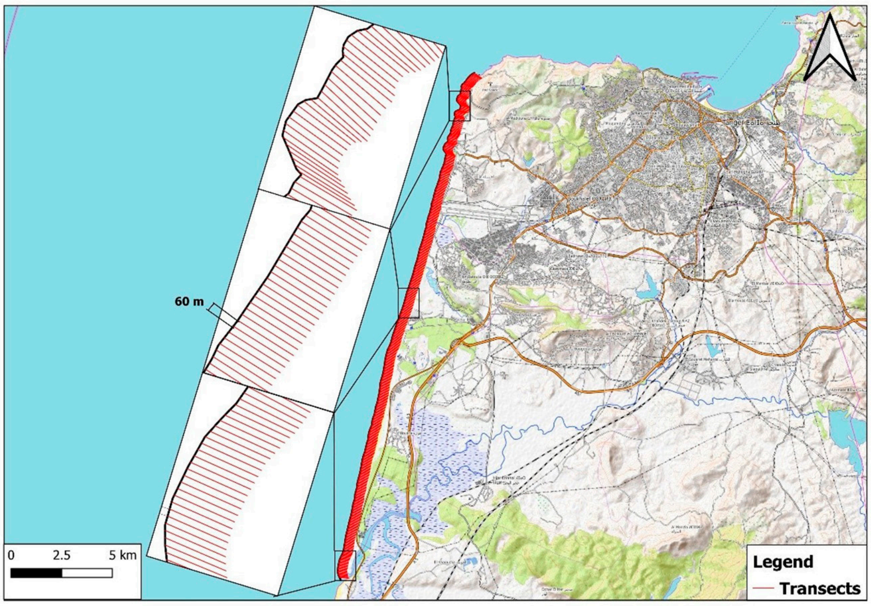

Fig. 4. – Transects generated by the Digital Shoreline Analysis System (1973–2024).

Following execution of the DSAS, the tool generates various quantitative outputs, including statistical indicators that characterize the magnitude, direction and consistency of shoreline movements over time. In this study, two key shorelines change rate estimators were used: the end-point rate (EPR) and the linear regression rate, offering complementary insights into the long-term dynamics of the Quang Nam coastline (Kabir et al. 2020).

The EPR is computed by dividing the distance between the oldest and most recent shoreline positions by the elapsed time between the two surveys. This converts net shoreline movement (NSM) into an annual rate of change, expressed in metres per year, and is particularly effective for evaluating linear shoreline displacement trends (Oyedotun 2014).

Short- and long-term trends (1973–2024) were analysed using the EPR (Sebat and Salloum, 2018) method (1), with intervals reflecting socio-environmental shifts. The results reveal accelerated erosion of the Tangier coastline since 1973.

$$\mathrm{EPR} = \frac{L_1 - L_2}{t_1 - t_2} \qquad (1)$$

where L1−L2 is the distance between the oldest and youngest coastlines, and t1 and t2 are the captured dates of the oldest and youngest coastlines.

The linear regression rate (2) is calculated by drawing a straight line through all shoreline positions over time, showing the average rate of change per year.

$$L = b + mx \qquad (2)$$

where L is a dependent variable denoting the spatial location of the shoreline, x is an independent variable of year, m is the slope, and b is the intercept, expressing the L change corresponding to the x change per unit. The positioning data collected during the field survey was first extracted from the Global Navigation Satellite Systems measurement device (Fig. 5) and projected onto the Google Earth map (Fig. 6); it then underwent specific processing in ArcGIS software to delineate a reference coastline as of July 3, 2024.

Fig. 5. – Topographic survey of Sidi Kacem Beach in 2024.

Fig. 6. – Shoreline of Sidi Kacem Beach in 2024.

RESULTS

The transects conducted along the Tangier coast revealed significant shoreline retreat between 1973 and 2024 (Fig.7). Erosion rates varied considerably along the coastline: the highest erosion rate of –5.64 m/year was observed at transect 523, while the lowest rate of retreat of only -0.022 m/year was recorded at transect 91. These differences highlight the uneven distribution of erosion processes along the Atlantic coast of Tangier.

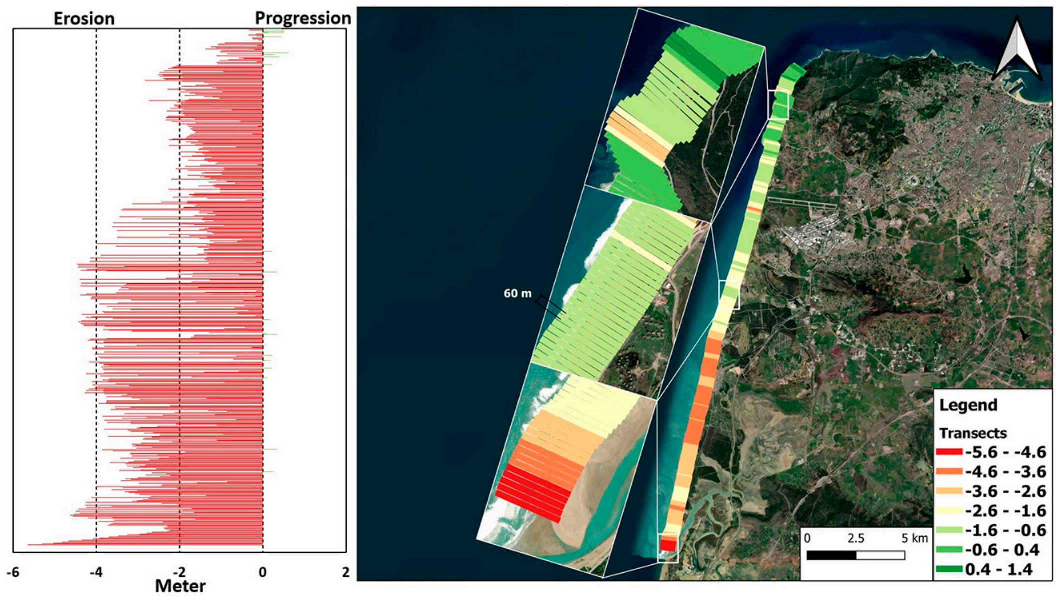

Fig. 7. – Overall evolution of the Tangier Atlantic Coastline (1973–2024).

In total, 350 transects were analysed along a north-south axis, enabling the identification of three distinct sections based on shoreline evolution trends. These sections offer a detailed understanding of coastal changes observed over the 51-year study period.

The EPR mobility index (Table 2), calculated using the DSAS model, was applied to 2-km-long segments of coastline. One segment included Achakkar Beach (35°46’13”N 5°56’04”W), where significant coastal accretion has been noted. The second segment included Sidi Kacem Beach (35°44’17”N 5°56’39”W) and El Hajryene Beach (35°42’49”N 5°57’06”W), both located in the central part of the study area. These beaches are experiencing erosion, although at lower intensities than other regions. Finally, the third segment corresponded to the southern portion of the Atlantic coastline near Tangier, specifically around Houara Beach. This area showed a pronounced trend of erosion, recording some of the highest erosion rates in the region (Fig. 8).

Table 2. – Statistics of end-point rate (EPR) shoreline changes.

EPR	Study areas	Erosion Zone	Accretion zone
Number of transects	523	495	28
Average shoreline mobility change rate (m year^{-1})	–2.24	–2.38	0.22
Minimum shoreline mobility change (m year^{-1})	–	–0.022	0.011
Maximum shoreline mobility change (m year^{-1})	–	–5.64	0.62
Percentage (%)	–	94.65	5.35
Transect with maximum erosion	523	523	–
Transect with maximum accretion	18	–	18

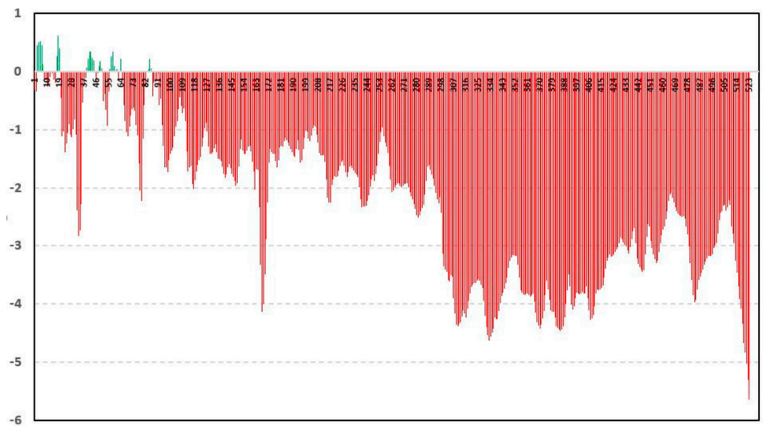

Fig. 8. – Kinematics of the coastline of the Atlantic coast of Tangier (1973–2024).

The linear regression rate index (Table 3) confirmed a general trend of erosion along the Atlantic coast of Tangier. The northern part showed slight accretion, while the central and southern parts showed mild and significant erosion, respectively. On average, the coastline retreated by –1.71 m year^{-1} across the entire study area. Of the 492 transects analysed, the majority (492) were in erosion-prone zones, with an average retreat of –1.84 m year^{-1}. Only 31 transects showed accretion, with an average gain of 0.35 m year^{-1}. The extreme values reveal considerable local variability, with erosion rates reaching up to –4.61 m year^{-1} and accretion rates up to 0.76 m year^{-1}. These results highlight a major coastal erosion phenomenon affecting most of the Atlantic coastline of Tangier during the study period.

Table 3. – Statistics of linear regression rates (LRR) for shoreline changes.

LRR	Study area	Erosion zone	Accretion zone
Number of transects	523	492	31
Average shoreline mobility change (m year^{-1})	–1.71	–1.84	0.35
Minimum shoreline mobility change (m year^{-1})	–	–0.014	0.013
Maximum shoreline mobility change (m year^{-1})	–	–4.61	0.76

Northern sector – Cape Spartel – the Hercules Caves

Bounded by Cape Spartel to the north and the Hercules Caves to the south, this zone includes Achakkar Beach (Fig. 9). The morphology of this area suggests a slight tendency toward sediment accumulation, with the shoreline gradually widening toward the edges. The evolution of the coastline between 1973 and 2024 shows minimal accretion, more pronounced between transects 39 to 51 and 59 to 65. On average, the shoreline advanced by 13 m, corresponding to an advancement rate of 0.020 m year^{-1}.

Fig. 9. – Coastline evolution in the Northern Sector (1973–2024).

Central sector – Sidi Kacem/El Hajryene

Located between the Hercules Caves to the north and extending approximately 7.3 km to the south (Fig. 10), this zone was characterized by mild erosion between 1973 and 2024. This erosion intensified progressively from north to south, with an average shoreline retreat of 92 m, corresponding to recession rates exceeding –1.80 m year^{-1}.

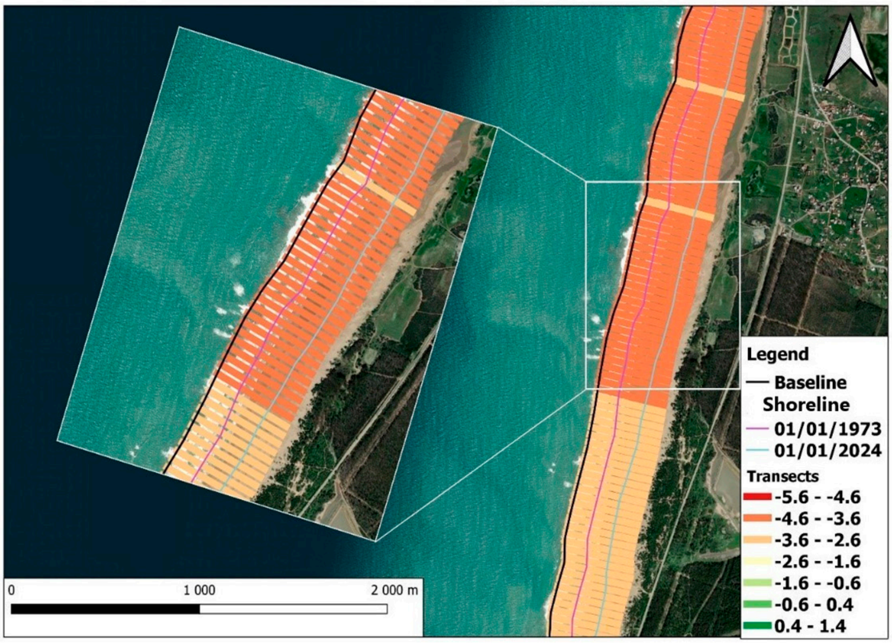

Fig. 10. – Coastline evolution in the Central Sector (1973–2024).

Southern sector – Houara

The analysis of shoreline changes between 1973 and 2024 (Fig. 11), based on 204 transects perpendicular to the coast, reveals a significant retreat at average rates ranging from –1.24 to –4.83 m year^{-1}. These variations indicate strong heterogeneity in coastal movements. The highest erosion was observed in the northern part (Fig. 11), opposite the Houara neighbourhood, where the retreat reached nearly 246 m, with the sands approaching the national road N2 at that point.

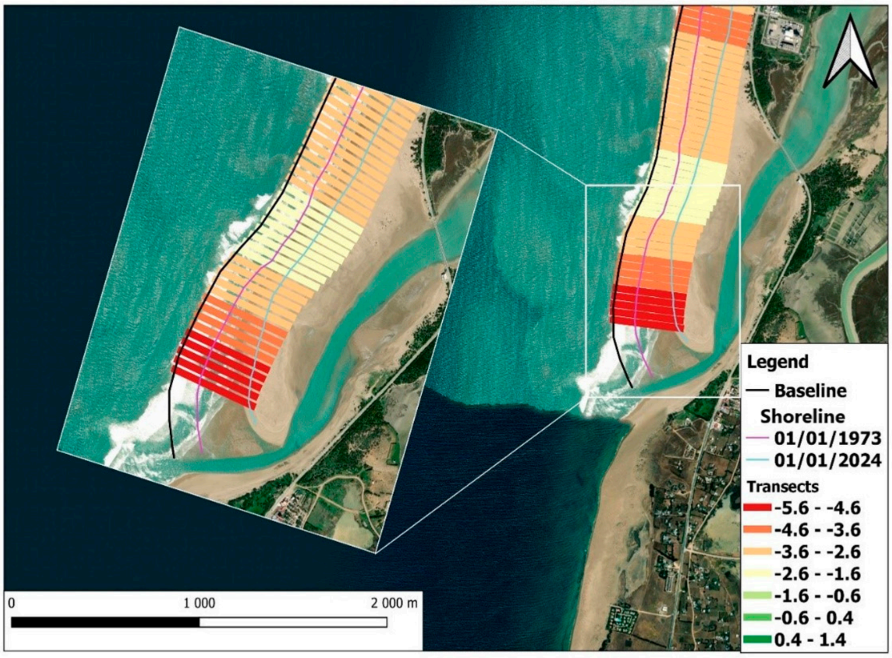

Fig. 11. – Coastline evolution in the Southern Sector (1973–2024).

Periodic evolution of the Sidi Kacem Beach shoreline

The period 1973-1990

Between 1973 and 1990, Sidi Kacem Beach underwent significant erosion, as indicated by the EPR and NSM indices (Fig. 12). The shoreline retreated by an average of 112.77 m, corresponding to a rate of –6.63 m year^{-1}. The maximum erosion rate was –8.61 m year^{-1}, observed at transect 46.

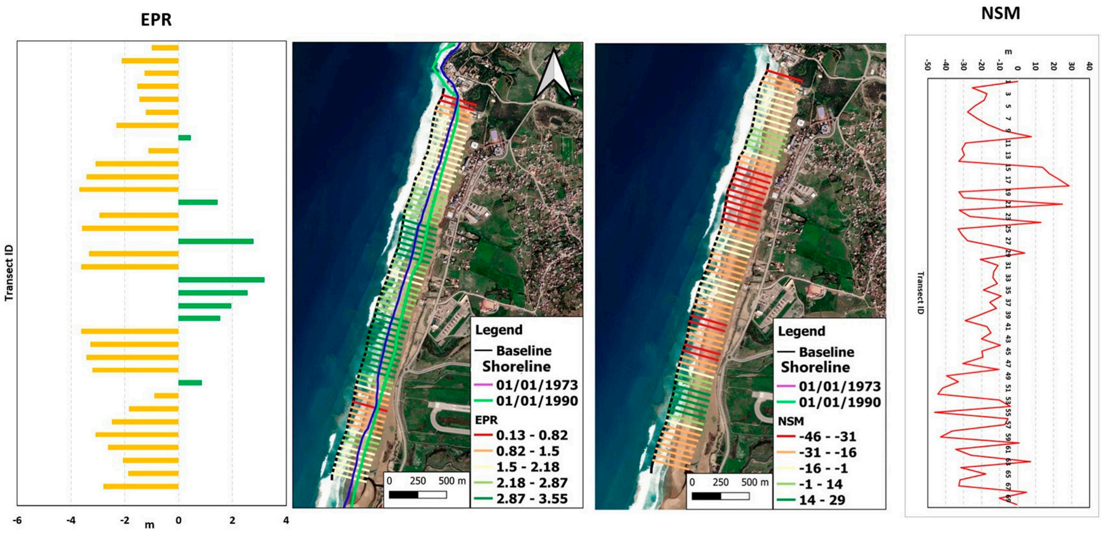

Fig. 12. – Coastline Evolution at Sidi Kacem Beach (1973–1990). EPR, end-point rate; NSM, net shoreline movement.

The period 1990-2015

From 1990 to 2015, the trend reversed, and the shoreline underwent accretion. The beach advanced at an average rate of 2.24 m year^{-1}, resulting in a total shoreline gain of 56.04 m. In some areas, accretion reached up to 88.82 m (Fig. 13).

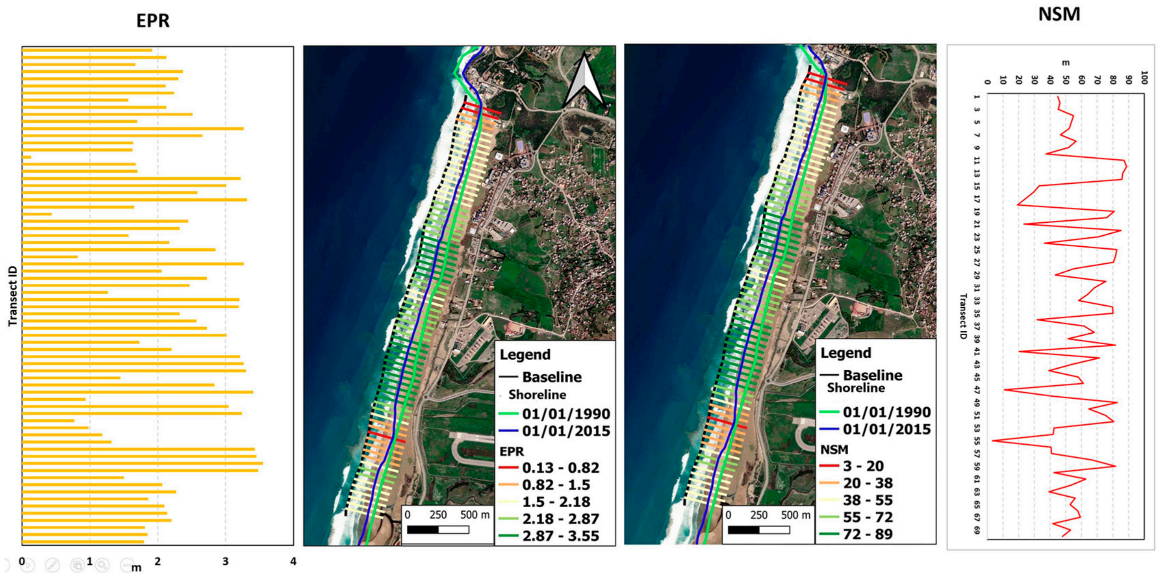

Fig. 13. – Coastline evolution at Sidi Kacem Beach (1990–2015). EPR, end-point rate; NSM, net shoreline movement.

The period 2015-2024

During the period 2015-2024, erosion was dominant in 59 transects, while accretion occurred in 11 transects (transects 12 to 15 and 54 to 62) (Fig. 14). The overall shoreline movement averaged –1.88 m year^{-1}, with an erosion rate of –2.51 m year^{-1} and an accretion rate of 1.47 m year^{-1}. The periodic erosion distance averaged –22.66 m, while accretion averaged 13.31 m). Though erosion dominated this period, localized areas still exhibited active sediment accumulation.

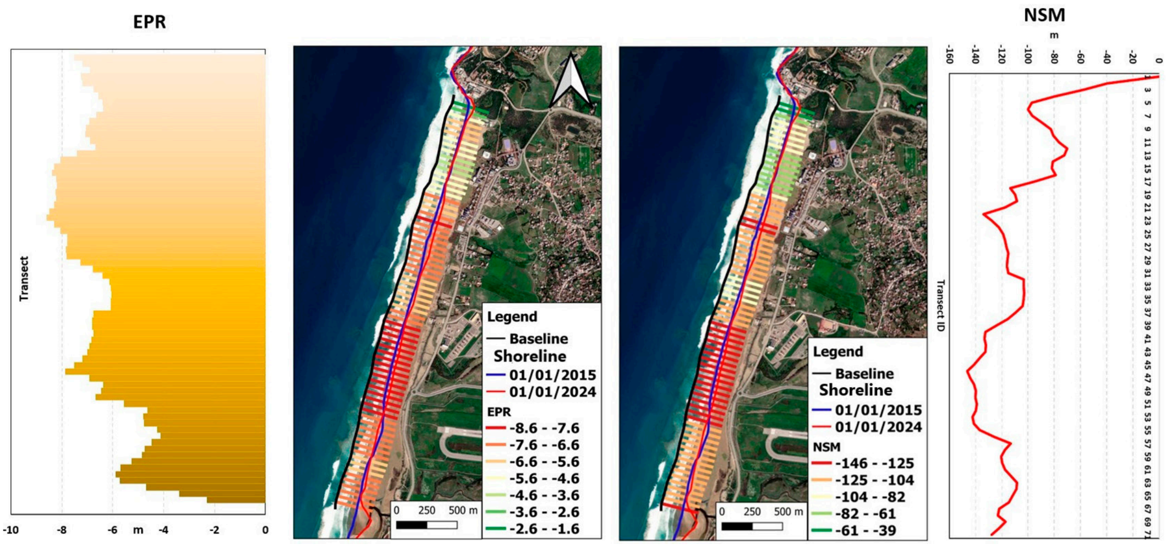

Fig. 14. – Coastline evolution at Sidi Kacem Beach (2015–2024). EPR, end-point rate; NSM, net shoreline movement.

Periodic evolution of the Houara Beach shoreline

The period 1976-1990

From 1973 to 1990, Houara Beach exhibited a clear erosional trend. All 83 transects analysed experienced erosion, with no sediment accretion being recorded. Erosion averaged –8.01 m year^{-1}, peaking at –10.48 m year^{-1}. The average periodic erosion distance was –136.31 m, with maximum values reaching –178.21 m (Fig. 15). These findings highlight severe and widespread coastal erosion throughout these 17 years.

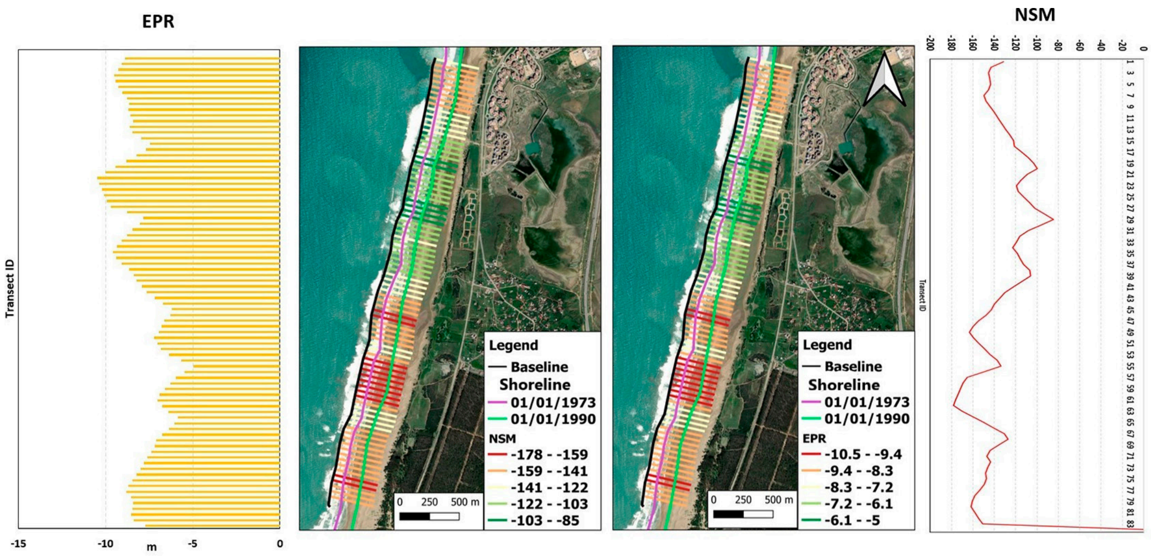

Fig. 15. – Spatio-temporal evolution of the shoreline of Houara Beach (1973-1990). EPR, end-point rate; NSM, net shoreline movement.

The period 1990-2015

Between 1990 and 2015, Houara Beach continued to experience extensive erosion, with all 83 transects being affected and no accretion being documented. The erosion rate averaged –2.12 m year^{-1}, peaking at –3.37 m year^{-1} (Fig. 16). Periodic erosion distances averaged –53.02 m, with maximum losses of –84.26 m. The absence of sediment accumulation highlights a persistent sediment deficit over these 25 years.

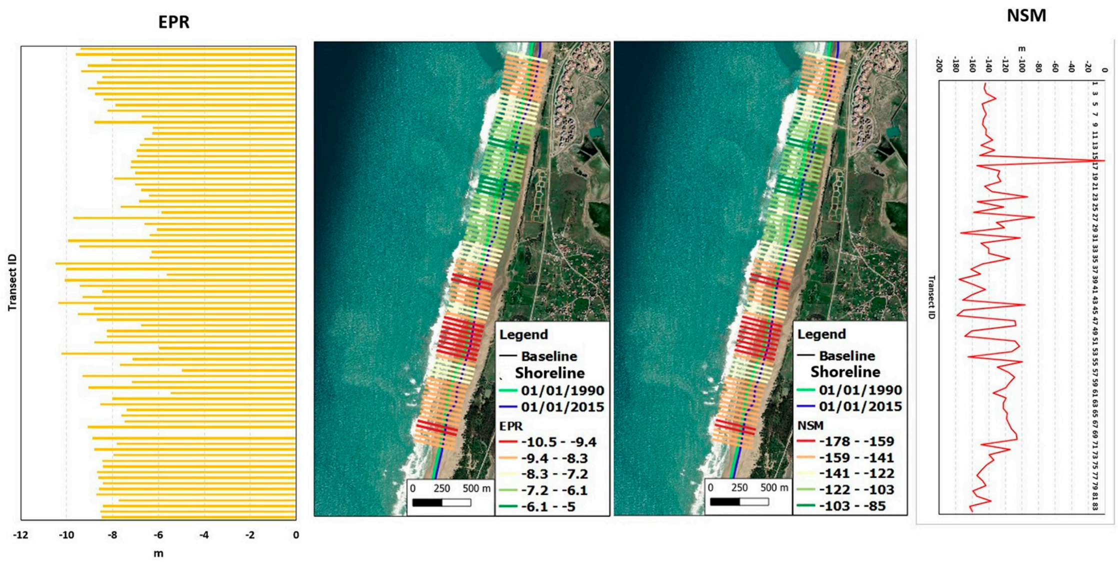

Fig. 16. – Spatio-temporal evolution of the shoreline at Houara Beach (1990–2015). EPR, end-point rate; NSM, net shoreline movement.

The period 2015-2024

Between 2015 and 2024, Houara Beach experienced mixed dynamics, with erosion affecting 46 transects and accretion affecting 37. The average shoreline change rate was –0.82 m $year^{-1}$, indicating an overall erosional trend. Erosion rates averaged –2.83 m $year^{-1}$, surpassing the accretion rate of 1.75 m $year^{-1}$ (Fig. 17). Periodic erosion distances averaged –25.52 m, exceeding the average accretion distance of 15.79 m. These findings demonstrate that coastal erosion remained predominant during this period, with shoreline losses significantly outweighing localized sediment gains.

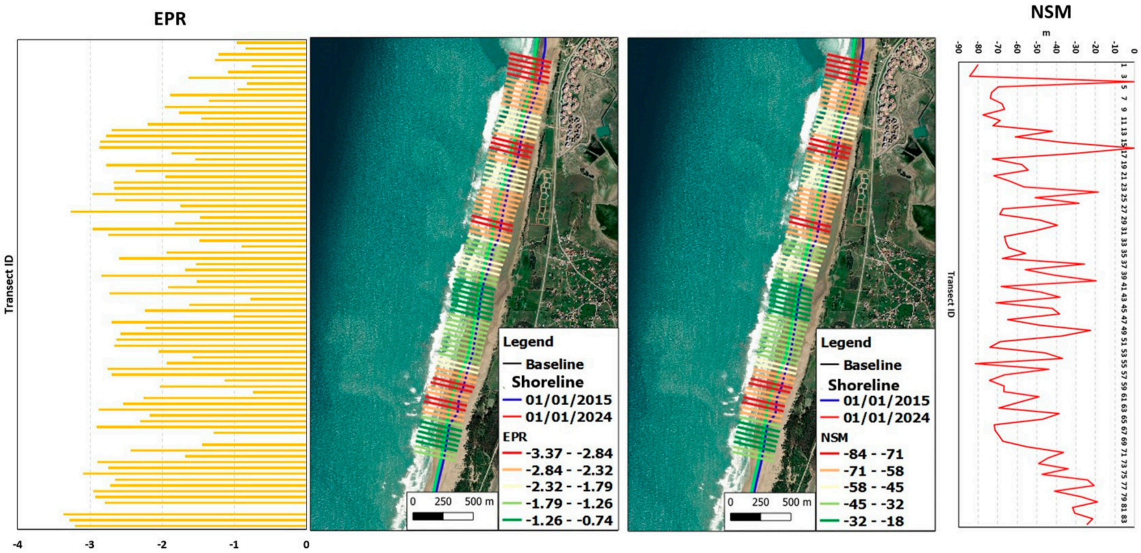

Fig. 17. – Spatio-temporal evolution of the shoreline at Houara Beach (2015–2024). EPR, end-point rate; NSM, net shoreline movement.

DISCUSSION

The analysis of coastal changes along the Tangier Atlantic coast between 1973 and 2024 revealed significant spatial and temporal variations in erosion and accretion patterns. The study area, extending approximately 25 km from Cap Spartel to Tahaddart, was classified into three distinct zones:

– The Northern Sector underwent minor accretion averaging 0.20 m $year^{-1}$, resulting in approximately 13 m of shoreline advancement. The relative stability observed here likely results from natural sediment deposition coupled with minimal human interference.

– The Central Sector, Sidi Kacem/El Hajryene, underwent moderate erosion at an average annual rate of –1.80 m $year^{-1}$. The patterns here reflect a combination of natural coastal processes and localized anthropogenic influences.

– The Southern Sector, Houara**,** underwent severe erosion at an average rate of –4.83 m $year^{-1}$, underscoring heightened vulnerability due to intense natural dynamics and substantial human pressures.

A detailed temporal analysis of two focal sites, Sidi Kacem (Zone 2) and Houara (Zone 3), revealed three distinct phases:

– 1973–1990: Marked by significant erosion, with annual shoreline retreats of –6.63 m $year^{-1}$ at Sidi Kacem and 8.01 m $year^{-1}$ at Houara. This intense erosion coincided with decreased sediment supply associated with dam construction (Ibn Battouta Dam, 1977) and prolonged drought conditions.

– 1990–2015: Exhibited fluctuations, with continuing erosion at Houara (–2.12 m $year^{-1}$), while Sidi Kacem experienced slight accretion (2.24 m $year^{-1}$). These variations may reflect natural sediment recovery or local management interventions.

– 2015–2024: Erosion and accretion rates decreased significantly, indicating possible stabilization, although the coastline remained degraded, with compromised sediment quality and habitat loss.

The observed coastal changes stem from a complex interplay of natural and human-driven factors. On the natural front, wave action and longshore currents continually redistribute sediments, while reduced sediment supply, exacerbated by recurring droughts, undermines this dynamic equilibrium. Compounding these pressures is sea-level rise, amplified by climate change, which accelerates coastal retreat.

Human activities play an equally decisive role. Rapid urbanization and infrastructure development along coastlines fragment ecosystems, while upstream dam construction disrupts the natural flow of sediments to downstream areas. This dynamic is worsened by excessive sand extraction for construction purposes, depriving beaches of material critical to their regeneration.

These erosional processes pose direct threats to coastal biodiversity, economic infrastructure and the safety of nearby communities. Addressing these challenges requires integrated management strategies: stricter sand extraction and urban sprawl regulation, sediment flow restoration through adaptive dam management and river revitalization, and nature-based solutions. The latter, such as dune rehabilitation, mangrove restoration and the creation of vegetated buffer zones, offer sustainable protection by harnessing ecosystems' self-regulating capacities. A synergy between technical interventions and ecological resilience thus emerges as the key to mitigating risks while preserving the vital functions of coastal landscapes. Although the DSAS provided valuable insights, methodological limitations exist, including dependency on satellite image quality and sensitivity to georeferencing errors. Future research should incorporate complementary datasets (e.g. field surveys and LiDAR) and advanced modelling techniques to improve accuracy.

CONCLUSION

This study highlights the complex dynamics of shoreline changes along the Tangier Atlantic coast over the past five decades, particularly emphasizing severe erosion in the southern sector. The findings underscore the urgency of implementing integrated coastal management strategies that balance environmental protection with socio-economic development. Continued monitoring, adoption of advanced technological tools, and adaptive management practices are crucial for mitigating coastal erosion impacts and enhancing resilience in response to ongoing climate change. These results underscore the need for continuous monitoring to ensure sustainable coastal management. After thoroughly analysing these coastal dynamics, it is essential to broaden our approach to the associated geological risks. Erosion processes and urbanization may exacerbate the instability of adjacent slopes, thereby promoting landslides.

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DECLARATION OF COMPETING INTEREST

The authors of this article declare that they have no financial, professional, or personal conflicts of interest that could have inappropriately influenced this work.

ETHICAL CONSIDERATIONS

All satellite imagery used in this study adheres to relevant data usage regulations and licensing agreements, ensuring compliance with ethical standards. This includes datasets from Sentinel-2 (ESA) and Landsat (NASA), which were processed in alignment with licensing terms.

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AUTHORSHIP CONTRIBUTION STATEMENT

Ali Hadek: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, review and editing. **Miriam Wahbi:** Data curation, Formal analysis. **Mohammed Hlal:** Conceptualization, Data curation, Investigation, Supervision, Writing – review and editing. **Mustapha Maatouk:** Visualization. **Hakim Boulaassal:** Methodology, Software, Visualization. **Omar El Kharki:** Project administration. **Alaoui Yazidi Otman:** Visualization.

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