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Assessing the Impact of Port Structure on Shoreline Evolution: Case Study of Tangier Med Port, Morocco

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ABSTRACT

Coastal development can significantly impact nearby shorelines, raising concerns about erosion and sustainability. This study investigated the long-term effects of the Tangier Med port on the coastlines of Dalia and Ksar Sghir beaches in Morocco using remote sensing techniques and the digital shoreline analysis system (DSAS). A multi-decadal approach analyzed shoreline changes for pre-construction (1988–2005) and post-construction (2004–2022) periods. The obtained findings reveal contrasting patterns. Ksar Sghir displayed accretion, due to port infrastructure disrupting natural sediment transport. Dalia beach exhibited a mixed response with ongoing erosion and localized accretion, influenced by the construction of a fishing port on the eastern side of the beach. To gain further insights into the future trajectory of these shorelines, a Kalman filter model was employed to predict shoreline positions for the year 2034 and 2044. These predictions highlight the potential for continued divergence between the beaches. Dalia beach faces potential infrastructure damage on the western side due to ongoing erosion, while the eastern side may require increased dredging to maintain fishing port access. Ksar Sghir beach, on the other hand, is projected to experience continued accretion with minimal anticipated negative impacts. This research offers valuable insights into the differential impacts of port development on adjacent coastlines. It highlights the importance of long-term monitoring and pre-construction data for understanding coastal interventions. Additionally, incorporating shoreline forecasting can aid in developing sustainable management strategies for both coastlines and port functionality.

Keywords: Morocco, Tangier Med, shoreline changes, digital shoreline analysis system.

INTRODUCTION

Coastal environments are dynamic landscapes constantly shaped by the interplay of natural processes and human activities. Port development, a vital component of global trade, can significantly impact these delicate ecosystems (Jansen, 2023). Shoreline erosion is a major concern associated with port construction, threatening coastal infrastructure, habitats, and livelihoods (Tsoukala et al., 2015). Understanding the complex interactions between port infrastructure and shoreline dynamics is crucial for sustainable coastal management and planning.

The impact of port development on nearby shorelines exhibits significant variability. Some studies report shoreline accretion in sheltered areas due to wave sheltering and sediment deposition (Minoubi, 2018; Salim et al., 2018). Conversely, others document increased erosion due to altered wave patterns caused by port infrastructure (Ali and El-Magd, 2016; Chapapría and Peris, 2021). This inconsistency highlights the need for further research to understand the specific mechanisms at play.

This study focused on the Tangier Med port complex, the largest Mediterranean port in Morocco, and its potential impact on the adjacent Dalia and Ksar Sghir beaches. These low-energy, micro-tidal beaches raise concerns about potential erosion due to altered wave patterns and sediment transport associated with port construction. While previous research highlighted the diverse outcomes of port development on shorelines, a nuanced understanding of the long-term effects on these specific beaches is lacking.

This research aimed to bridge this knowledge gap by employing a multi-temporal approach to analyze shoreline changes at Dalia and Ksar Sghir beaches. The digital shoreline analysis system (DSAS) within a geographic information system (GIS) framework was utilized. By analyzing historical imagery spanning from 1988 to 2022, the erosion rates for both pre-construction and post-construction periods were quantified. Furthermore, the DSAS capabilities to perform shoreline forecasting were leveraged, aiming to predict the future positions of the shorelines and assess the long-term influence of port structures on these beach dynamics.

STUDY AREA

The Tangier Med port complex, a major infrastructure development on the southern shoreline of the Strait of Gibraltar, is located approximately 26 kilometers east of Tangier, Morocco (Fig. 1). Its construction commenced in June 2006 and unfolded in two phases: Tangier Med I (operational since 2007) and Tangier Med II (operational since 2019). This study focused on two coastal sections within the complex vicinity: Ksar Sghir to the west and Dalia to the east.

The study area lies within the Rif mountain range, specifically the Rifain Domain (Saadi, 1982). This domain extends across northern Morocco, encompassing the coastal region from the Straits of Gibraltar to the Moulouya wadi. Notably, the area falls within the Arc of Gibraltar, a complex geological structure formed by the collision of the African and Iberian tectonic plates. This distinctive formation includes the Betic Cordillera in southern Spain, the Strait of Gibraltar connecting the Atlantic to the Mediterranean, and the Rif Mountains in northern Morocco.

In terms of specific coastal characteristics, Dalia beach presents a trapezoidal morphology, featuring a noteworthy width surpassing 145 m in its western section. With a total length measuring approximately 730 m, this shoreline segment displays considerable spatial dimensions. Conversely, the Ksar Sghir beach exhibits an arc-shaped configuration, with a width spanning 65 m and an extensive length surpassing 980 m, emphasizing its distinctive physical attributes.

Dalia Beach draws sediment from the Tisirène formations, resulting in fine-grained sand and suspended clay particles. Ksar Sghir Beach is nourished by the Ksar Sghir River, which flows through

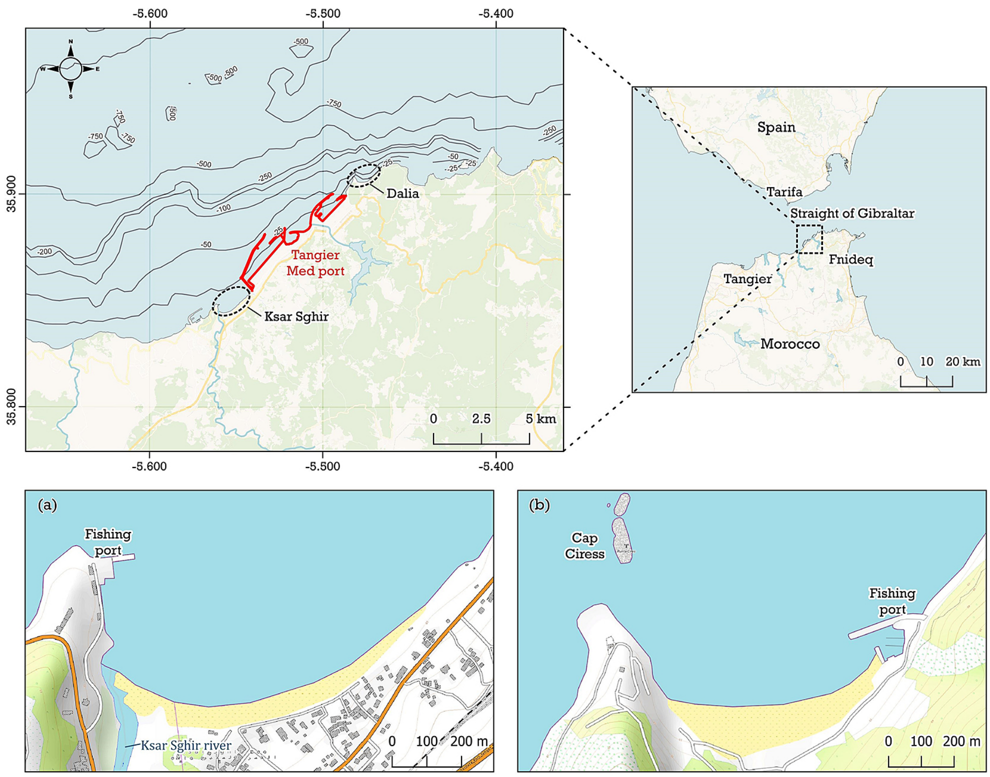

Figure 1. Study area (a) Ksar Sghir (b) Dalia

various geological formations, leading to a sandy and clayey sediment composition. Importantly, the seabed throughout the studied coastal zone features a solid and resistant nature (IDOM, 2006).

The region's Mediterranean climate is characterized by precipitation from Atlantic disturbances (Azores) and, less frequently, Mediterranean disturbances. Saharan influences create hot and dry winds, including the Chergui and Sirocco, blowing from the East and Southeast.

The hydrodynamic regime is influenced by Atlantic swells from the west-northwest, with average wave heights reaching 0.5 meters. During winter storms, these swells can intensify, reaching heights of 3 meters and generating stronger nearshore currents, particularly southward towards the sheltered bay of Ksar Sghir. The tides in the area are semi-diurnal, fluctuating twice daily with an average range of 2.5 meters (Fig. 2). This predominantly Mediterranean influence leads to relatively calm water levels during slack tides, followed by moderate currents during tidal shifts.

MATERIALS AND METHODOLOGY

The analytical approach employed in this study relied on photo-assisted computer interpretation, a methodology extensively explored and documented by numerous researchers. This method consisted of a three-step procedure, commencing with data preparation, followed by shoreline extraction and change rate calculation, and concluding with the estimation of errors.

Data preparation

To analyze shoreline movement, a multi-source imagery dataset was acquired, encompassing both orthorectified aerial photographs from the National Agency for Cadastre, Land Registry, and Cartography in Morocco (ANCFCC) and satellite imagery from the United States Geological Survey (USGS) website. Selection prioritized high spatial resolution (ideally below 5 meters) and appropriate temporal coverage encompassing

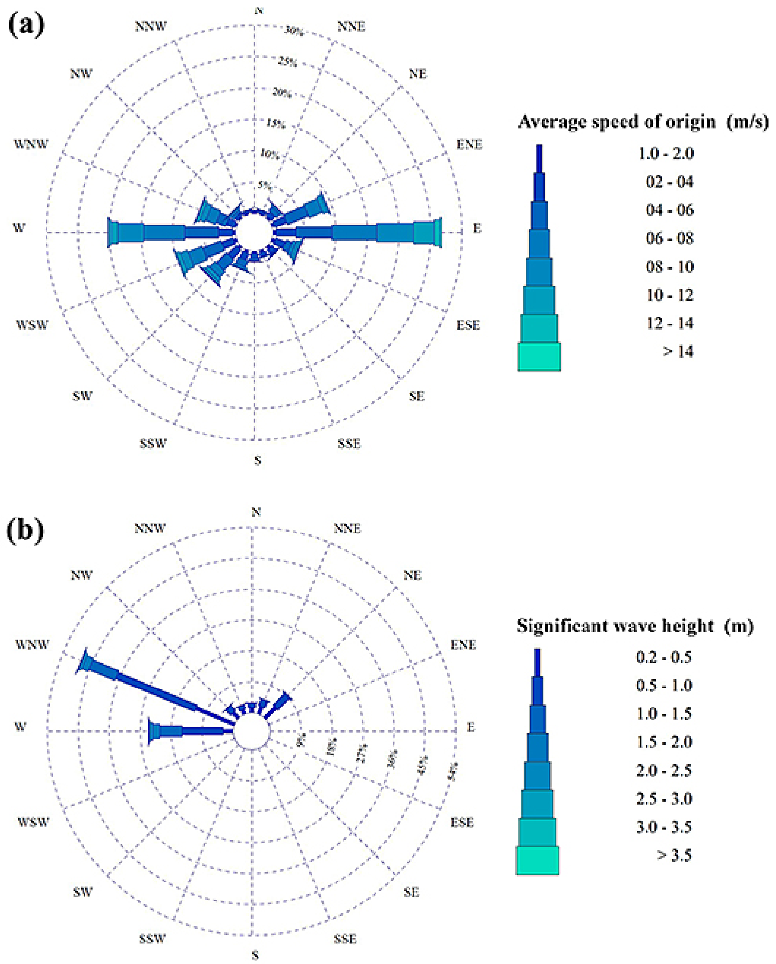

Figure 2. (a) Wind rose, (b) wave rose of the study area (2005–2022) (www.puertos.es)

both pre-construction and post-construction periods (detailed in Table 1). This ensures accurate capture of intricate shoreline features and isolates potential project impacts. All imagery underwent rigorous preprocessing to enhance quality and geospatial accuracy. This included radiometric calibration for consistent color and brightness, geometric corrections to address distortions, atmospheric corrections to minimize haze, and orthorectification to precisely represent features on the Earth's surface, crucial for precise shoreline measurement.

Shoreline extraction

Choosing a consistent and representative reference line is critical for accurate shoreline change analysis across all data sets. This line should effectively capture the long-term evolutionary trends of the coastline. Identifying the optimal reference line necessitates a meticulous examination of all images used in the study. Ideally, the chosen marker should be readily identifiable and consistently present throughout the various datasets. In this study, two prominent lines were consistently observed across all analyzed aerial photographs: the instantaneous shoreline and the mean sea level (MSL) line. However, due to the lack of data on corresponding tide heights, utilizing the instantaneous shoreline as a reference line proved impractical. Consequently, the high water line (HWL) was chosen as the primary reference line. HWL represents the highest water level reached during a tidal cycle. While acknowledging that HWL can vary depending on specific locations and weather conditions, its presence is typically more readily identifiable than the mean high water line (MHWL) in aerial imagery, particularly without access to tide height data. This selection offers a consistent and relatively clear marker for analyzing shoreline change over time.

Shoreline change rate quantification and forecasting

The digital shoreline analysis system (Himmelstoss et al., 2021) was employed to quantify shoreline changes. DSAS is a software add-in for ArcGIS that facilitates shoreline change analysis by calculating rate-of-change statistics from multiple historical shorelines. This enables the capture of variations in coastline morphology over time. The effectiveness of the software for shoreline change detection is well-documented (Nassar et al., 2019; Salim et al., 2021; El Habti et al., 2022; Bourhili et al., 2023; Rumahorbo et al., 2023). DSAS utilizes a baseline measurement method (Leatherman and Clow, 1983) to calculate the shoreline change rates. Transects, perpendicular lines intersecting the shorelines, are automatically generated at set intervals (20 meters in this study) to create measurement points. These points are then used to calculate shoreline change rates using two common methods:

- Net shoreline movement (NSM): this is the simple distance between the oldest and most recent shorelines at each transect (measured in meters).
- End point rate (EPR): this method calculates the average annual shoreline movement by dividing the shoreline displacement by the time elapsed between the oldest and most recent shorelines. Its advantages include ease of calculation and minimal data requirements (only two shorelines needed). However, it disregards information from intermediate shorelines if available.

Table 1. Data used for shoreline analysis

	Type	Source	Date	Scale/Resolution
Dalia	Aerial photo	ANCFCC	09/01/1988	1/30000
	Satellite image	Orbview-3	07/27/2004	1 m
	Satellite image	ESRI Living Atlas	09/19/2014	< 1 m
			09/18/2019	
			09/21/2022	
Ksar Sghir	Aerial photo	ANCFCC	09/01/1988	1/30000
	Satellite image	Orbview-3	10/11/2005	1 m
	Satellite image	ESRI Living Atlas	09/19/2014	< 1 m
			09/18/2019	
			09/21/2022	

- Linear regression rate (LRR): can be calculated by adjusting a least squares regression line to all shoreline points along a specific transect. This regression line is positioned to minimize the sum of squared residuals, which involves squaring the distance of each data point from the regression line and summing these squared residuals. The rate of change, or slope, of the linear regression line represents the linear regression rate.

Error estimation

Shoreline mapping encounters various uncertainties influencing the rate of shoreline change, as highlighted by Fletcher et al. (2003). These uncertainties arise from four main types of errors: pixel error (Ep), georeferencing error (RMSE) (Eg), digitization error of the reference line (Ed), and oscillation error of the high-water line (Eo). To gauge the overall uncertainty in determining coastline position, the Global coastal position error (Ecp) is computed, involving the square root of the sum of squared errors. This comprehensive measure, annualized as Eα, provides an estimate of error across the entire study period.

$$Ecp = \sqrt{Ep^2 + Eg^2 + Ed^2 + Eo^2} \quad (1)$$

$$E\alpha = \frac{\sqrt{Ep^2+Eg^2+Ed^2+Eo^2}}{Periode} \quad (2)$$

The following table summarizes the calculated errors (Table 2).

Shoreline forecasting

Shoreline forecasting with DSAS utilizes the Kalman filter (Kalman, 1960) to predict future positions. This method merges the observed historical data with predictions from shoreline change models. The Kalman filter, initialized with a linear regression rate from DSAS, estimates shoreline position and change rate every 10 years. It also provides an uncertainty estimate to acknowledge the inherent complexity of shoreline dynamics. However, limitations exist. Models may not capture all factors, leading to potential inaccuracies. Additionally, the linear regression assumption for future trends might not always hold true.

RESULTS AND DISCUSSION

This study investigated the impact of the Tangier Med port on the coastline by analyzing two distinct monitoring periods. The pre-construction phase establishes the baseline shoreline condition, enabling to isolate the potential effects of the port. Following construction, the study quantified the immediate shoreline modifications caused by this major project. By examining both pre- and post-construction phases, this research aimed to offer valuable insights into the coastal dynamics of the Tangier Med region. Furthermore, leveraging the post-construction shoreline change patterns, a 10-year and 20-year shoreline forecast was conducted to predict the future coastline position. This comprehensive approach provides valuable information for developing improved management and planning strategies for these ever-changing coastal areas.

Pre-construction phase (1988–2005)

The digital shoreline analysis system analysis of pre-construction shoreline change for both Dalia and Ksar Sghir beaches reveals extensive erosion (Fig. 3). At Dalia beach, all 58 transects (100%) experienced erosion, with the average net shoreline movement being -33.27 meters. However, the erosion was not uniform across the beach. While the overall average suggests significant retreat, the maximum retreat reached -45.23 meters, likely concentrated on the eastern side of the beach based on transect locations. This spatial variability is further reflected in the end point rate (EPR) which averaged -2.01 meters per year. Statistically significant erosion was evident across all transects.

Similarly, Ksar Sghir beach exhibited erosion at all 54 analyzed transects (100%). The average NSM for Ksar Sghir was -36.74 meters, with a maximum retreat of -50 meters. Here, EPR

Table 2. Errors associated with coastline position

Forecasting	Dalia					Ksar Sghir				
Shoreline	1988	2004	2014	2019	2022	1988	2005	2014	2019	2022
Ecp	5.46	4.02	4.00	3.99	2.98	5.88	4.28	4.36	3.73	3.05
Eα	0.27					0.28				

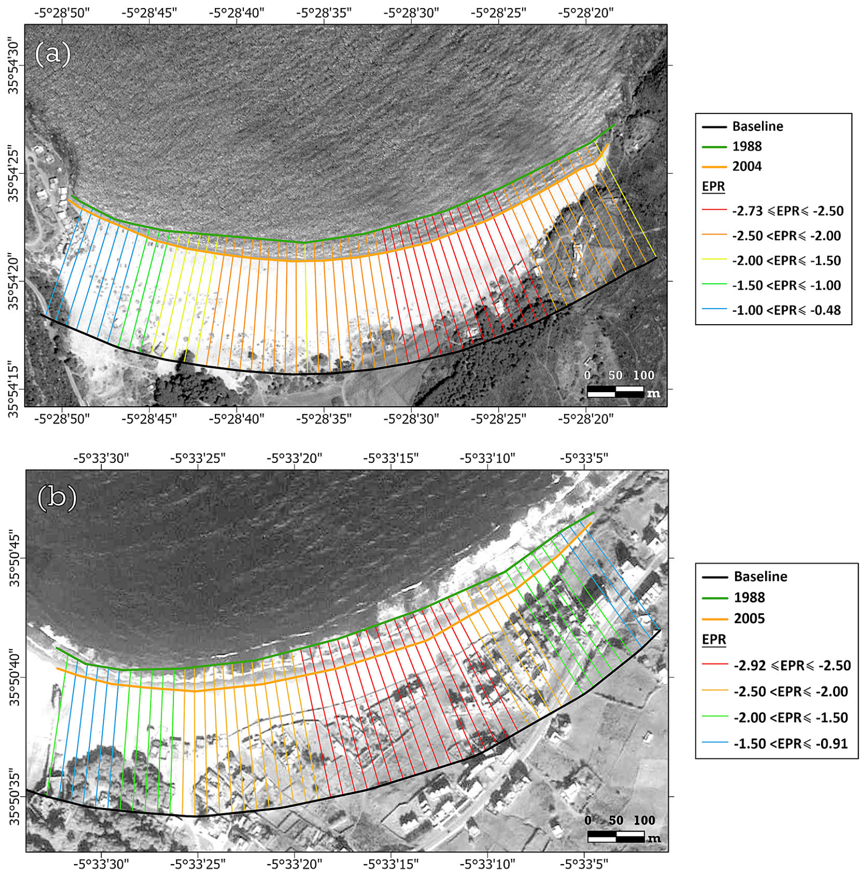

Figure 3. EPR-based map of shoreline evolution (pre-construction) for (a) Dalia (b) Ksar Sghir Beaches

indicates an average erosion rate of -2.15 meters per year, with the highest erosion rates concentrated in the median part of the beach based on transect locations. Due to the dynamic nature of the shoreline near the Ksar Sghir river mouth, it was excluded it from analysis. This exclusion is necessary to ensure an accurate representation of the overall change rate. All transects again showed statistically significant erosion. These findings highlight a dominant trend of erosion along both beaches during the pre-construction period, though with some spatial variation within each beach.

Post-construction phase (2004–2022)

The analysis reveals distinct shoreline change patterns at Dalia and Ksar Sghir beaches during the post-construction period (Fig. 4).

The evolution pattern in Dalia beach indicates a trend of erosion across most transects (75.44%), with an average NSM of -10 meters based. However, some variability exists, with a portion of transects (24.56%) experiencing accretion by up to 56.91 meters in the Eastern side, This accretion phenomenon, observed subsequent to 2014, coincided with the establishment of a fishing port along the eastern expanse of Dalia beach. The transverse breakwater construction associated with the fishing port impeded sediment transport, thereby fostering sand accumulation. Linear regression rate suggests an average erosion rate of 0.52 meters per year, statistically significant erosion was identified in only 20% of transects.

In contrast, Ksar Sghir beach shows a clear trend of accretion. The average NSM is a positive 17.41 meters, indicating an overall shoreline advance. Only a small percentage of transects (5.56%) experienced erosion, with a maximum retreat of just 3.52 meters. This dominance of accretion is translated to LRR, with an average accretion rate of 0.82 meters per year, although statistically significant accretion was found in only 7.41% of transects.

It is important to note that the authors opted to utilize LRR instead of end point rate for this analysis. This choice was made due to the inclusion of four shoreline dates (2004, 2014, 2019, and 2022). LRR is a more robust method for analyzing shoreline change trends when multiple data points are available, as it considers the overall

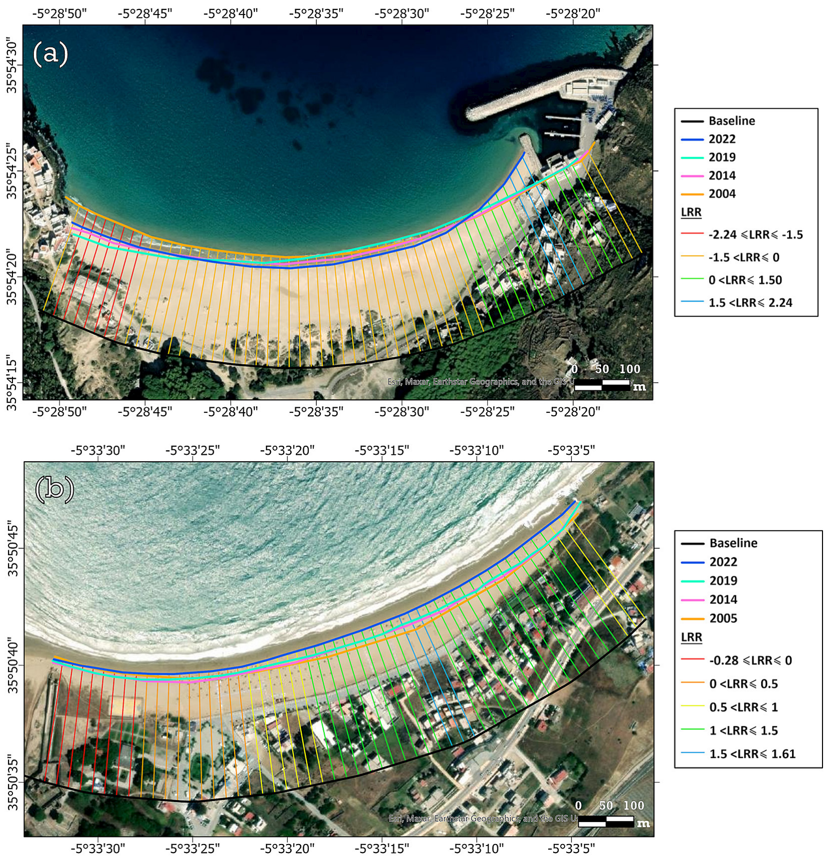

Figure 4. LRR-based map of shoreline evolution (post-construction) for (a) Dalia (b) Ksar Sghir Beaches

rate of change across the entire post-construction period, rather than simply focusing on the difference between the first and last shorelines.

Shoreline forecasting

The predictive beta forecast generated by the Kalman filter model provides insights into the anticipated shoreline dynamics for the years 2034 and 2044. Notably, at Dalia beach, an ongoing trend of erosion is evident along its western coastline, where projections indicate that the shoreline will encroach upon the vegetation line and potentially impact nearby houses. Conversely, on the eastern side of Dalia beach, an accretion process is anticipated to occur, extending towards the port access channel. This progression may necessitate dredging activities to maintain navigability, prompting authorities to initiate preparatory measures in the affected area. In contrast, Ksar Sghir beach exhibits a distinct pattern, with accretion observed along a substantial portion of its shoreline. Despite this change, no significant adverse effects on local infrastructure have been identified.

DISCUSSION

The examination of shoreline changes before and after the construction of the Tangier Med port offers valuable insights into the complex interactions between natural processes and human interventions shaping coastal environments (Table 3). During the initial period, both Dalia and Ksar Sghir beaches experienced erosion, primarily driven by natural forces, such as wave action, tidal currents, and longshore drift. This period serves as a baseline, highlighting the natural variability of coastal morphology in the absence of significant anthropogenic influences. The absence of substantial human-made structures underscores the dominant role of natural processes in driving shoreline retreat during this time.

Following the construction of the Tangier Med port, a noticeable shift towards accretion was observed at Ksar Sghir beach. This accretion is attributable to the disruption of eastward sediment transport (littoral drift) driven by the prevailing westerly and west-northwesterly currents. The port structures act as a substantial barrier, effectively altering the natural trajectory of

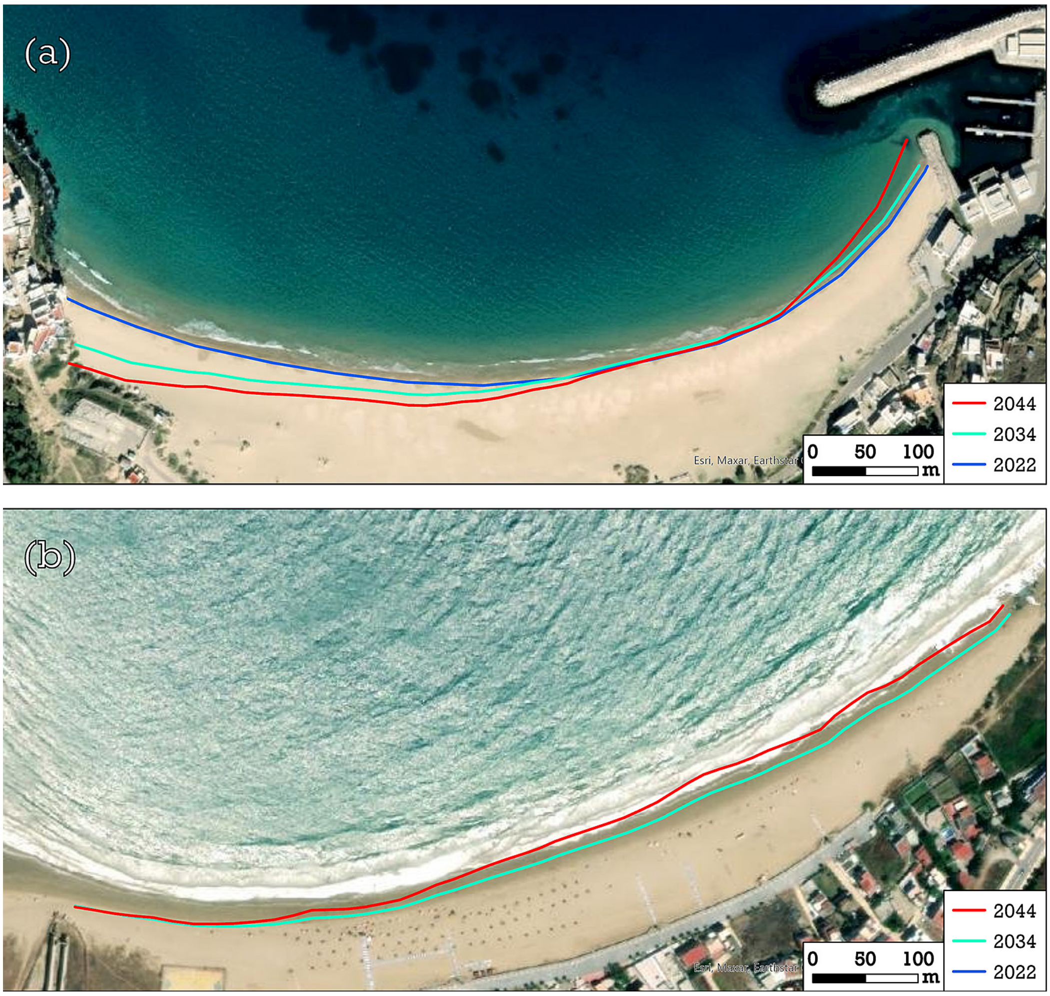

Figure 5. The predicted shoreline position of 2034 and 2044, (a) Dalia (b) Ksar Sghir

sediment. As a consequence, sediment accumulates on the Ksar Sghir side of the port, manifesting in the observed accretion.

In contrast, Dalia Beach exhibits a more nuanced response to the Tangier Med port construction. The western side shows minimal influence from the port due to two key factors. Firstly, Cap Ciress, located on Dalia's western edge, acts as a natural barrier, effectively sheltering the coastline from the full impact of port-induced changes in wave patterns and sediment transport. Secondly, the seabed on the western side is composed of hard bedrock with rapid water depth changes, limiting the availability of readily transportable sediment, which exacerbate the ongoing erosion observed. Conversely, the eastern side of Dalia Beach displays a clear trend of accretion demonstrably linked to the construction of a fishing port (after 2014) with a transverse breakwater. This breakwater disrupts eastward longshore sediment transport, causing sand to accumulate on Dalia's eastern shore.

The 10-year and 20-year shoreline forecasts provide valuable insights for developing long-term coastal management strategies. The predicted continuation of erosion on the western side of Dalia Beach highlights the potential for future infrastructure damage. Proactive measures, such as beach nourishment or the construction of protective structures, may be necessary to safeguard coastal assets and mitigate the impacts on nearby houses. The anticipated accretion on the eastern side suggests a potential need for increased dredging activities to maintain the port access channel's navigability. Early planning and budgeting for these dredging operations will be crucial for ensuring continued port functionality. Conversely, the projected accretion at Ksar Sghir Beach suggests minimal intervention may be required for the near future. However, ongoing monitoring of shoreline changes at all locations remains essential to ensure the effectiveness of implemented management strategies and to adapt them as needed (Table 3).

Table 3. Shoreline evolution statistics

Study area	Dalia				Ksar Sghir			
Period	Pre-construction		Post-construction		Pre-construction		Post-construction	
Indice	NSM (m)	EPR (m/yr)	NSM (m)	LRR (m/yr)	NSM (m)	EPR (m/yr)	NSM (m)	LRR (m/yr)
Transect	58	58	57	55	54	54	54	54
Average coastal mobility	-33.27	-2.01	-10	-0.52	-36.74	-2.15	17.41	0.82
Maximum erosion	-45.23	-2.73	-32.98	-2.24	-50	-2.92	-3.52	-0.28
Maximum accretion	0	0	56.91	2.24	0	0	30.88	1.61
Erosional transects	58	58	43	41	54	54	3	8
Accretional transects	0	0	14	14	0	0	51	46

CONCLUSIONS

The main objective of this study was to investigate the impact of the Tangier Med port on the coastlines of Dalia and Ksar Sghir beaches in Morocco, utilizing a multi-decadal approach and remote sensing techniques. The study aimed to analyze shoreline changes during two distinct periods: pre-construction (1988–2005) and post-construction (2004–2022), to isolate the potential influence of port development on coastal dynamics. The Digital Shoreline Analysis System (DSAS) was employed alongside various data sources, including orthorectified aerial photos, OrbView-3 satellite images, and Esri's Living Atlas imagery. This comprehensive approach allowed for a detailed examination of shoreline evolution and prediction of future shoreline positions using a Kalman filter model.

The pre-construction phase established the baseline shoreline condition, providing insight into natural shoreline processes before port development. DSAS analysis revealed extensive erosion along both beaches, highlighting the predominant role of natural factors such as wave direction and sediment transport in driving shoreline retreat. Following the port's construction, contrasting patterns emerged, with Ksar Sghir showing a shift towards accretion while Dalia beach exhibited a more complex response. The analysis of post-construction shoreline changes revealed a nuanced interplay of factors, including the influence of port infrastructure on littoral drift and the protective barrier effect of Cap Ciress.

The shoreline forecasting for 2034 and 2044 provided valuable insights into future coastal dynamics, emphasizing the need for proactive management strategies to mitigate potential impacts. The projected erosion on Dalia Beach's western side underscores the importance of infrastructure protection measures, while the anticipated accretion on the eastern side necessitates careful planning for port maintenance activities. Similarly, ongoing monitoring of shoreline changes at both locations remains essential to ensure the effectiveness of implemented management strategies and adapt them as needed, contributing to the sustainable management of coastal areas and port facilities in the Tangier Med region.

These findings underscore the importance of understanding local characteristics and specific timeframes in assessing coastal evolution. By analyzing the distinct patterns of shoreline changes at Dalia and Ksar Sghir beaches over different periods, this study highlighted the dynamic nature of coastal environments and the need for tailored management strategies. The contrasting responses observed post-construction emphasize the complexity of coastal dynamics and the importance of considering site-specific factors in coastal planning and management. This holistic approach, integrating long-term monitoring, remote sensing techniques, and predictive modeling, provides valuable insights into the future trajectory of coastal evolution, enabling proactive measures to safeguard coastal assets and promote sustainable development in coastal regions.

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