Assessing the coastal impact of port development and dredging activities. Tangier Med port. Morocco

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Abstract

The construction of the Tangier Med port complex, Morocco's largest Mediterranean port, ignited concerns about its impact on nearby Dalia and Ksar Sghir beaches. This study investigated the morphodynamic changes of these beaches to determine the port's influence on their shoreline dynamics.

Employing a multi-temporal approach, we analyzed shoreline changes across two distinct periods: 1988-2022 (pre- and post-construction) and 2013-2022. The first period leveraged aerial photographs, satellite imagery, and the Digital Shoreline Analysis System (DSAS) within a comprehensive Geographical Information System (GIS) framework. Erosion rates were quantified using established indices (NSM, EPR, LRR).

Intriguingly, DSAS revealed a consistent erosive trend across the entire period, but with significantly higher rates before port construction. This suggests a potential stabilizing effect of the port complex and associated offshore dredging, potentially mitigating the impact of frequent storms and intense waves observed in the earlier period.

Detailed topographical surveys in 2012 and 2022 corroborated these findings, revealing overall coastal stability with minor fluctuations attributed to meteorological and riverine factors. This highlights the complex interplay between human-induced infrastructure development and natural forces in shaping these beaches' evolution.

This study underscores the critical need to consider both natural and anthropogenic factors in coastal management and planning. While the Tangier Med port complex and dredging may have contributed to shoreline stabilization, neglecting the influence of natural events, particularly in the pre-construction phase, could lead to inaccurate assessments and potentially unsustainable coastal development.

Keywords: Morocco, Tangier Med, Shoreline, Sandy Beaches, GIS, DSAS, DGPS.

Introduction

Port infrastructure and offshore dredging operations play pivotal roles in the global maritime trade and overall development efforts. Nevertheless, these activities also exert substantial influences on coastal environments, specifically sandy beaches.

Sandy beaches represent dynamic systems in constant flux due to both natural and human-induced factors. Natural elements, including waves, currents, tides, and storms, fundamentally mold and sustain the characteristics of sandy beaches. Concurrently, human interventions, such as the construction of port structures and offshore dredging, can significantly reshape beach morphology and dynamics.

Port facilities, including structures like breakwaters, jetties, and groins, possess the capacity to disrupt wave patterns and sediment movement, leading to processes of beach erosion and accretion. Offshore dredging operations similarly wield considerable influence, as they involve the extraction of sand from the coastal system and the perturbation of sediment transport patterns.

The impact of port structures and offshore dredging on sandy beaches emerges as a multifaceted and intricate issue. The degree of impact hinges on a multitude of variables, encompassing the nature and magnitude of the port development, the physical and biological attributes of the beach, and the prevailing environmental conditions. Numerous studies have been conducted to assess the changes brought about by the implementation of these types of structures (ALEMAN et al., 2012; Bertier, 2009; Jeudy De Grissac, 1979; Minoubi, 2018).

In recent times, heightened awareness has arisen concerning the potential adverse effects of port structures and offshore dredging on sandy beaches. Nevertheless, a pressing need persists for expanded research endeavors that can yield a deeper comprehension of the intricate dynamics inherent in these systems and subsequently formulate effective strategies for mitigation. Assessments are essential to ensure the sustainable and responsible execution of offshore dredging activities.

The primary objective of this research is to investigate how the Tangier Med port complex, along with offshore dredging activities in the Northwestern region of Morocco, influences the morphological transformations of the nearby sandy beaches, namely Ksar Sghir and Dalia. To assess this impact, our study adopts a geomatic approach, involving the assessment of shoreline evolution by scrutinizing aerial photographs and satellite images, utilizing Geographic Information System (GIS) tools coupled with the Digital Shoreline Analysis System (DSAS). Additionally, we analyze the morphological profiles of these beaches through the implementation of Differential Global Positioning System (DGPS) surveys.

Study area

The Tangier Med port complex is located on the southern shoreline of the strategically significant Strait of Gibraltar, approximately 26 km east of Tangier. Within the purview of this study, the investigation focuses on two distinct coastal sections, namely Ksar Sghir and Dalia, located respectively west and east of the port (Fig.1).

The study area finds its geographical positioning within the Rif mountain range, encompassed by the renowned Rifain Domain (Saadi, 1982). This domain spans the northern territories of Morocco and extends across the region from the Straits of Gibraltar to the mouth of the Moulouya wadi (East of Morocco), showcasing an expansive coverage within the country.

Of particular relevance, the study zone lies within the prominent Arc of Gibraltar, an intricate geological structure that owes its existence to the convergence and subsequent collision between the African and Iberian tectonic plates. This distinctive formation is shaped by the interplay of various landforms, including the Betic Cordillera located in the southern parts of Spain, the Strait of Gibraltar acting as a vital conduit, and the Rif Mountains, which grace the northern regions of Morocco.

The sand composition of each beach is generally unique. Dalia Beach receives sediment inputs from the Tisirène formations, which provide fine grains and suspended clay particles. Ksar Sghir Beach is nourished by the Oued Ksar Sghir, which flows through the sandy and clayey formations of the Beni Ider and Tisirène aquifers, as well as the Pliocene-Quaternary formations. The predominant characteristic of the seabed along the major part of the studied coastal zone is its solid and resistant nature (IDOM, 2006).

The region has a mediterranean climate. Precipitation primarily stems from two sources: Atlantic disturbances (Azores), bringing moist air masses to the Rif region, and Mediterranean disturbances (linked to the arrival of cold air masses from the North), less frequent but typically humid. Additionally, this area is subject to the influence of Saharan pressures, resulting in the hot and dry winds of Chergui and Sirocco, blowing from the South and Southeast.

The hydrodynamic regime is controlled by the action of Atlantic swells, arriving from the west-northwest with average wave heights reaching 0.5 meters. During winter storms, however, these swells can intensify, reaching heights of 3 meters and generating stronger nearshore currents, particularly southward towards the sheltered bay of Ksar Sghir. Tides in the area are semi-diurnal, meaning they fluctuate twice daily with an average range of 2.5 meters. This predominantly Mediterranean influence results in relatively calm water levels during slack tides, followed by moderate currents as water levels rise and fall.

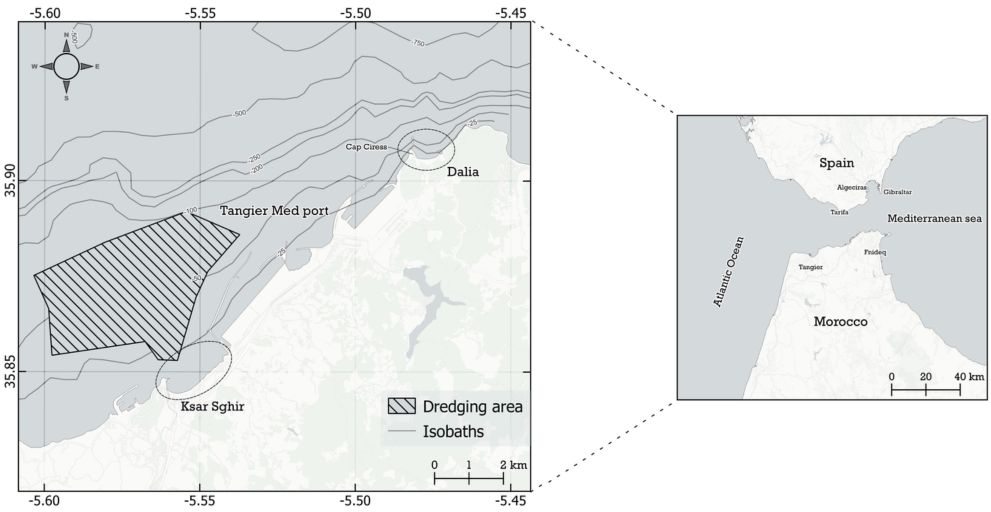

Figure 1: Study area (bathymetry data : GEBCO 2021).

Materials and methodology

The methodology is grounded on two key indicators: a comprehensive analysis of shoreline movement spanning 35 years (1988-2022) through photo interpretation and a decade-long evaluation (2013-2022) focusing on morphological variability by tracking cross-sectional topographic profiles.

Shoreline movement

Data preparation

After acquiring aerial photos and satellite images, and ensuring that the spatial resolution and temporal coverage of the imagery are sufficient to accurately capture coastal features (Table 1), we proceed to perform the necessary preprocessing steps on the data. These steps include radiometric and geometric corrections, atmospheric correction, and orthorectification. These steps aim to enhance the image quality and align it with the Earth's surface.

	Source	Year	Scale / Resolution
Dalia	Aerial photo	1988-09-01	1/30000
	Orbview-3	27/07/2004	1m
	Google Earth	27/09/2022	0.6m
Ksar Sghir	Aerial photo	1988-09-01	1/30000
	Orbview-3	2005-11-10	1m
	Google Earth	29/11/2022	0.6m

Table 1: Used data

Shoreline extraction

It is imperative that the selected reference line is consistent for all available data and best reflects the evolution trends. Defining this line is a demanding task that requires a careful examination of all photographs used to choose the most appropriate marker for each section of the studied coast.

Across all images used in this study, two lines are clearly recognizable in each of them: the instantaneous shoreline and the high-tide line. Due to the unavailability of corresponding tide height data, using the instantaneous shoreline as a reference line proved unsuitable for this research. Therefore, the choice was made in favor of the high-tide line. This line represents the level reached on the foreshore by the high tide during the entire slack water period, commonly referred to as foreshore wetting lines.

Computation of shoreline movement

The variations in the evolution of the coastline were directly quantified using the Digital Shoreline Analysis System (Himmelstoss et al., 2021). DSAS is an add-in for the Esri ArcGIS desktop and is selected for its ability to monitor, display, and map shoreline advancement or retreat over both short-term and long-term periods. It also enables the estimation of rate-of-change statistics by analyzing multiple shoreline positions, thereby capturing variations in coastline morphology. this tool have proven it's effectivnes in tracking shoreline changes in numerous studies (El Habti et al., 2022; Moussaid et al., 2015; Salim et al., 2021; Sarwar & Woodroffe, 2013).

DSAS employs a baseline measurement method to calculate change rate statistics for a time series of shorelines (Leatherman & Clow, 1983). The baseline serves as the starting point for all transects established by the DSAS application. Transects intersect each shoreline to create a measurement point, and these measurement points are used to calculate shoreline change rates. In our case, transects are automatically generated with a uniform spacing of 20 meters, and their number varies from one site to another.

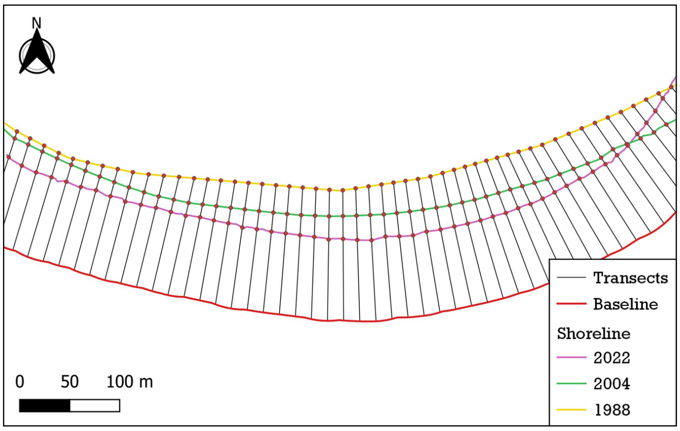

Figure 2: An output from DSAS analysis of the study area showing the baseline, transects and the historical shorelines.

The detection of variations in shoreline position is a widely explored research area, with numerous methods available in the scientific literature. Among the predominant approaches adopted by researchers, two main methods stand out: the end-point rate method for characterizing periodic evolution patterns and linear regressions for estimating change rates over the entire study period.

Taking these factors into consideration, we have chosen to use the following three indices to better understand shoreline evolution at the site:

- Net Shoreline Movement (NSM): the distance between the oldest and most recent shoreline for each transect, and the units are in meters;
- End Point Rate (EPR): calculated by dividing the shoreline displacement distance by the time elapsed between the oldest and most recent shoreline. The main advantages of EPR are ease of calculation and the minimal requirement of only two shoreline dates. The disadvantage is that in cases where more data is available, additional information is ignored;
- Linear Regression Rate (LRR): This can be determined by fitting a least squares regression line to all shoreline data points for a given transect. The regression line is positioned to minimize the sum of squared residuals (calculated by squaring the offset distance of each data point from the regression line and summing the squared residuals). The rate of change of the linear regression is the slope of the line.

Uncertainty and errors estimation

Several sources of error factors can influence the accuracy of coastline position data and, consequently, impact the results of analyses in coastal monitoring studies (El Habti et al., 2022; Crowell et al., 1991; Durand, 2002;

Fletcher et al., 2003; Moore et al., 2006). These errors are mainly related to the quality of collected data and their processing. Four types of errors have been identified in this kinematics.

Pixel error, linked to the spatial resolution of the images, indicates that lower resolution may reduce precision in determining the coastline position. Georeferencing error arises due to the modest quality of certain photographs, leading to inaccuracies in tidal lines and introducing uncertainty in precisely locating the coastline. Overlay or alignment errors are assessed by the software using the root mean square of the squares of the deviations (RMS). Digitization error, averaging the maximum deviations during inputting coastline positions, introduces uncertainty when different operators perform repeated digitizations, resulting in variations in coastline identification. Tidal fluctuation error emphasizes the importance of obtaining satellite images simultaneously under comparable tidal conditions in comparative studies of shoreline movement, this practice minimizes the influence of fluctuations in high-water levels. The primary margin of error affecting the accuracy of the mean high water line is defined by the horizontal gap (H) between the position of maximum high water and that of minimum high water.

The cumulative measure of these errors, known as Global Coastal Position Error, is determined by taking the square root of the sum of the squares of each specific error type and represents the overall uncertainty in determining coastline positions.

$$Ecp = \sqrt{Ep^2 + Eg^2 + Ed^2 + Et^2} \;\; and \;\; E\alpha = \frac{Ecp}{Period\ (t)}$$

Ecp: Global Coastal Position Error ;

Ep: Pixel error (spatial resolution) ;

Eg: Georeferencing error (RMS) ;

Ed: Digitization error ;

Et: Tidal fluctuation error ;

Eα: Overall average error in m/year.

The following table summarizes the calculated errors:

Dalia			
Year	1988	2004	2022
Global Coastal Position Error	5.9	2.03	2.36
Period	1988 - 2004	2004 - 2022	1988 - 2022
Overall average error in m/year	0.35	0.11	0.07
Ksar Sghir			
Year	1988	2005	2022
Global Coastal Position Error	6.27	4.25	3.68
Period	1988 - 2005	2005 - 2022	1988 - 2022
Overall average error in m/year	0.35	0.24	0.11

Table 2: Error margins associated with coastline position.

Topographic survey

As for the morphological indicator, cross-sectional profiles of the two beaches, Ksar Sghir and Dalia, were carried out using the SinoGNSS T300 GNSS receiver. These profiles were then compared with the survey results conducted in 2013 by the Laboratory of Environment, Oceanology, and Natural Resources at Abdelmalek Essaâdi University. The aim was to analyze and evaluate any changes in the beach profiles over time, providing insights into the morphological dynamics of the beaches.

The fundamental concept of topographic surveying of beach profiles lies in measuring the coordinates at each point where a topographical change in slope occurs. Profiles established at different dates are examined to illustrate and quantify morphological and volumetric changes. These distinct measurements are obtained through the implementation of a protocol involving several steps.

In preparation for our regular monitoring missions, we took certain steps to facilitate upcoming operations. This included positioning fixed markers along the cornice and identifying markers on the dunes in areas where no cornice was present. These markers were designated as starting points for each profile, while a reference point with known coordinates (X, Y, Z) was located for DGPS calibration.

The DGPS station was set up on the aforementioned reference point, ensuring its configuration and the flatness of the measurement surface.

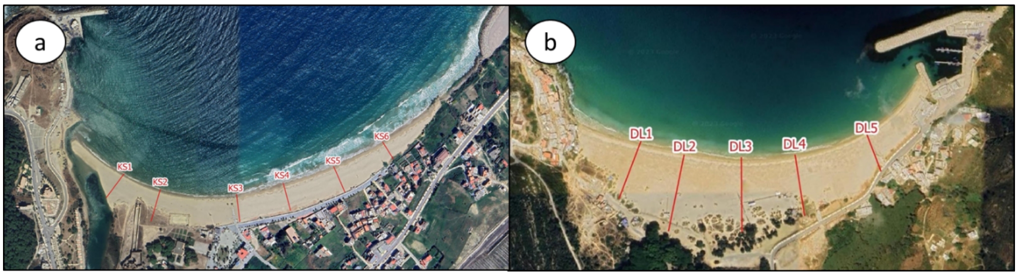

Figure 3: Profiles position along the beach (a) Ksar Sghir and (b) Dalia.

Results and discussion

Shoreline movement

This multi-temporal framework allows for a comprehensive analysis of shoreline evolution, taking into account both short-term impacts and long-term trends. By examining the pre- and post-construction eras of the Tangier Med port, the study can assess the immediate effects of the port's development on the coastline. Additionally, the long-term perspective provides a broader understanding of coastal dynamics, considering natural and human influences over time.

The medium-term periods before and after the port's construction enable the identification of specific changes triggered by the infrastructure, while the long-term period allows for the differentiation of natural and human-induced coastal modifications. This approach is crucial for evaluating the sustainability of coastal developments and understanding the complex interactions between natural processes and human activities.

Pre-construction phase

Beyond the Tangier Med port, the coastal evolution of both Dalia and Ksar Sghir beaches is evident.

During the initial monitoring period from 1988 to 2005, the results for both beaches depict notable trends in coastal changes (Tables 3). The analysis of Net Shoreline Movement (NSM) indicates a substantial average retreat, reaching approximately -34.32 meters for Dalia and -31.81 meters for Ksar Sghir. The most significant retreat observed for Dalia and Ksar Sghir beaches reached values of -44.65 meters and -43.03 meters, respectively.

Simultaneously, the analysis of End Point Rate (EPR) for both beaches reveals average annual erosion rates of approximately -1.93 meters per year for Dalia and -1.92 meters per year for Ksar Sghir. The maximum erosion rate recorded was -2.51 meters per year for Dalia and -2.6 meters per year for Ksar Sghir.

Post-construction phase

Throughout the second phase of monitoring, the results of Net Shoreline Movement (NSM) recorded an overall average coastal retreat of -16.5 in Dalia, with 89.8% of transects displaying negative distances, signifying prevalent erosion. The most substantial recession reached was -30.79 meters. In contrast, Ksar Sghir exhibited an overall average shoreline advance of 3.06 meters during the same period, with 66.13% of transects recording positive distances, indicating a significant predominance of coastal accretion. The combined NSM results underscore the divergent coastal dynamics between the two beaches, with Dalia experiencing notable erosion and Ksar Sghir exhibiting a notable trend of accretion.

	Dalia		Ksar Sghir	
	NSM (m)	EPR (m/yr)	NSM (m)	EPR (m/yr)
Transect	56	56	61	61
Average coastal mobility	-31.81	-1.92	-34.32	-1.93
Maximum erosion value	-43.03	-2.6	-44.65	-2.51
Maximum accretion value	0	0	0	0
Erosional transects	56	56	61	61
Accretional transects	0	0	0	0

Table 3: Coastal Evolution Metrics (NSM & EPR) of Dalia and Ksar Sghir (1988-2005).

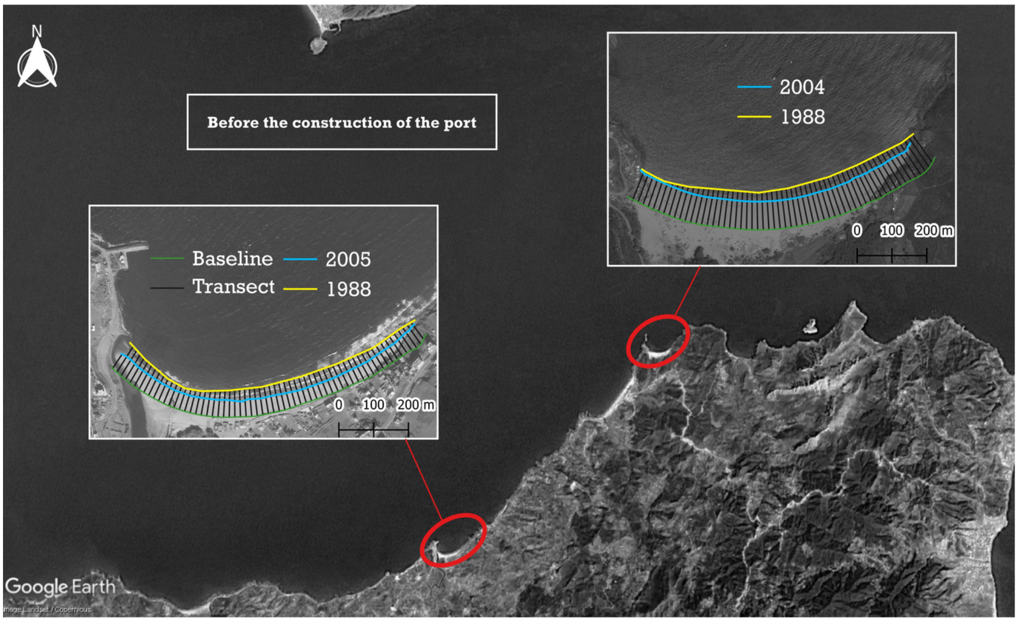

Figure 4: Cartographic representation of shoreline movement of Dalia ana Ksar Sgir (1988 - 2005).

Turning to the analysis of End Point Rate (EPR), the combined results for Dalia and Ksar Sghir during the second monitoring phase revealed an average erosion rate of -0.92 meters per year for Dalia, with 79.59% of transects showing statistically significant erosion and 8.16% exhibiting significant accretion. The presence of sediment gains east of Dalia was noteworthy. Conversely, Ksar Sghir displayed an average annual shoreline advance of 0.18 meters, with none of the transects exhibiting erosion or accretion rates reaching significant values. The combined EPR outcomes further emphasize the contrasting coastal behavior, with Dalia experiencing notable erosion rates and sediment dynamics and Ksar Sghir demonstrating an overall trend of shoreline advance with limited incidence of erosion (Tables 4 and 5).

	Dalia		Ksar Sghir	
	NSM (m)	EPR (m/yr)	NSM (m)	EPR (m/yr)
Transect	49	49	62	62
Average coastal mobility	-16.5	-0.92	3.06	0.18
Maximum erosion value	-30.79	-1.72	-6.44	-0.38
Maximum accretion value	47	2.62	10.7	0.63
Erosional transects	44	44	21	21
Accretional transects	5	5	41	41

Table 4: Coastal Evolution Metrics (NSM & EPR) of Dalia and Ksar Sghir (2004 - 2022).

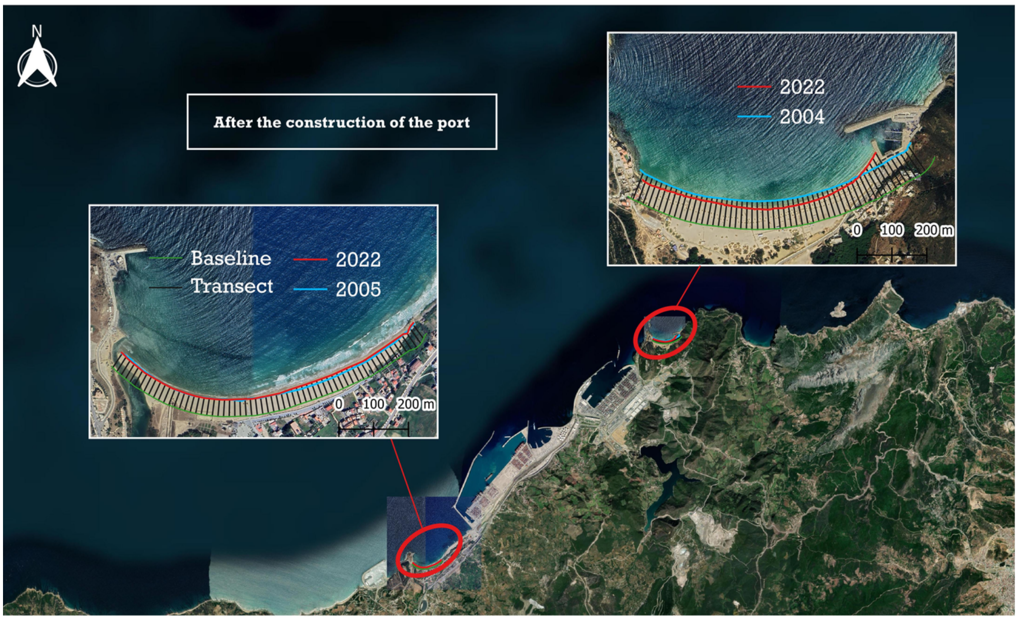

Figure 5: Cartographic representation of shoreline movement of Dalia ana Ksar Sgir (2004 - 2022).

Long-term period

In the comprehensive long-term analysis spanning from 1988 to 2022, the combined assessment of Net Shoreline Movement for both Dalia and Ksar Sghir beaches reveals distinct patterns in coastal evolution.

The findings for Dalia Beach indicate a noteworthy average retreat of -6.25 meters over the studied period, with 98.21% of transects exhibiting negative distances, signifying prevalent coastal erosion. The maximum recession observed was -68.99 meters, while only 1.79% of the transects displayed slight accretion, with a maximum positive distance of 8.54 meters.

In parallel, the results for Ksar Sghir Beach illustrate a more extensive average shoreline retreat of approximately -31.23 meters. All 61 transects uniformly recorded negative distances, emphasizing widespread coastal erosion, with a maximum recession of -47.24 meters.

Examining the End Point Rate analysis, Dalia Beach displayed an average erosion rate of -1.45 meters per year, with 92.86% of the transects exhibiting statistically significant erosion. The peak erosion rate reached -2.2 meters per year, and a small portion (1.79%) demonstrated slight accretion.

For Ksar Sghir Beach, the EPR results revealed an average shoreline retreat of approximately -0.9 meters per year. Notably, 98.36% of the transects showed statistically significant erosion, emphasizing the substantial impact of erosion processes in the study area. The highest erosion rate recorded was -1.36 meters per year.

Finally, the analysis of LRR indicated an average retreat of -1.41 meters per year for Dalia Beach, with 97.96% of transects demonstrating erosion. The maximum erosion rate recorded was -1.99 meters per year, and only a small portion (2.04%) exhibited slight accretion, though not statistically significant.

Conclusion

After carefully examining the results of the overall coastline evolution, a clear trend of erosion emerges. However, when comparing the two periods (before and after the construction of the Tangier Med port complex), it is interesting to note that erosion rates were higher during the first period. This observation raises several explanatory hypotheses:

Hypothesis 1: Natural Factors Favoring Erosion. It is possible that natural factors played a more significant role

	Dalia NSM (m)	EPR (m/yr)	LRR (m/yr)	Ksar Sghir NSM (m)	EPR (m/yr)	LRR (m/yr)
Transect	49	49	49	62	62	61
Average coastal mobility	-16.5	-0.92	-1.41	3.06	0.18	-0.91
Maximum erosion value	-30.79	-1.72	-1.99	-6.44	-0.38	-1.37
Maximum accretion value	47	2.62	0.28	10.7	0.63	0
Erosional transects	44	44	48	21	21	61
Accretional transects	5	5	1	41	41	0

Table 5: Coastal Evolution Metrics (NSM, EPR, LRR) of Dalia and Ksar Sghir (1988 - 2022).

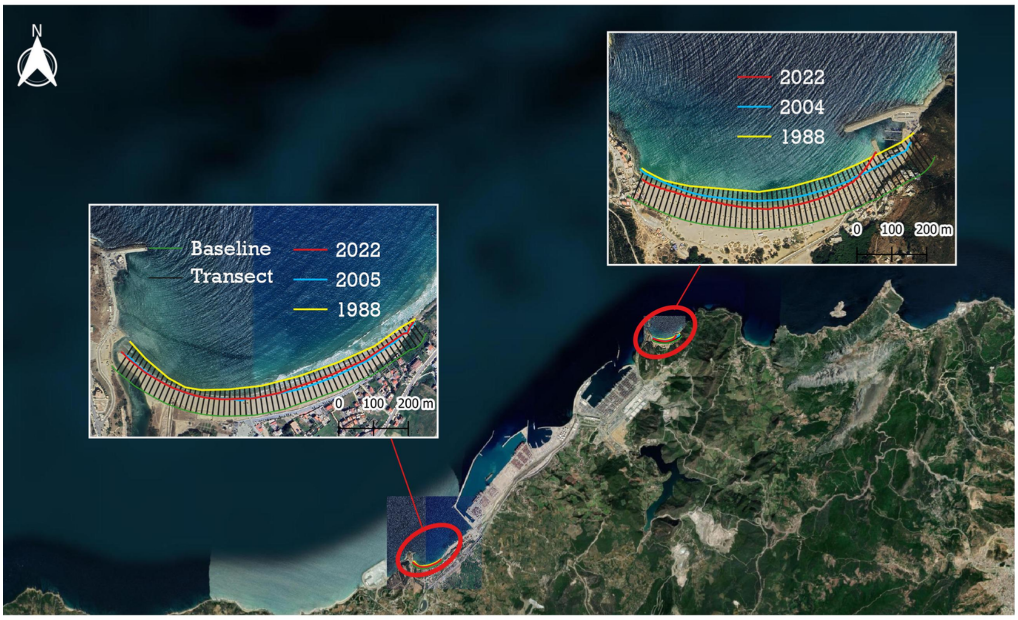

Figure 6: Cartographic representation of shoreline movement of Dalia ana Ksar Sgir (1988- 2022).

during the first period. The first period may have been characterized by a higher frequency of disruptive natural events such as storms, violent waves, or sea-level rises. These phenomena can induce more substantial coastal erosion by disrupting the shoreline.

Hypothesis 2: Stability after Infrastructure. The construction of the Tangier Med port complex and offshore dredging operations may have contributed to stabilizing the coastline during the second period. Port structures can act as natural coastal defenses by limiting erosion. Additionally, dredging activities could have redistributed sediments in a way that reduces erosion.

Topographic survey

Dalia

The Dalia Beach is characterized by a trapezoidal geomorphological configuration, with a width exceeding 145 meters in its western part. This beach extends over a total length of approximately 730 meters. To study its characteristics and dynamics in more detail, five profiles were established and numbered from 1 to 5, from west to east. These profiles were strategically positioned to cover the entire beach, enabling a comprehensive analysis of its topographic variations and behavior over time.

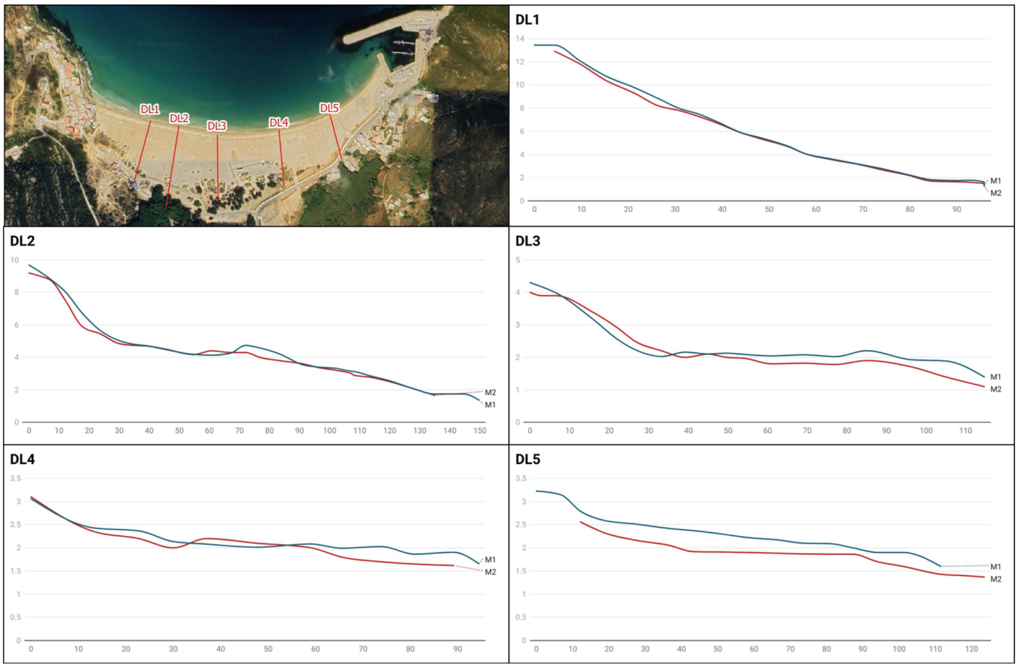

Figure 7: Dalia Beach Profiles.

Profile DL1: The western section of the beach shows a sand accumulation resulting from the influence of winds, forming a sloping incline characterized by an overall average gradient of 15.1%. The elevation above sea level at the top of the profile reaches 12.9 meters.

Comparison between the two profiles does not reveal significant variation in terms of the overall shape of the slope or elevation relative to the local mean sea level. However, localized variations were observed compared to the profile from the first survey, but the sand volumes remain essentially the same. This apparent stability could be explained by fluctuations resulting from wind action, which alters surface morphology in certain areas.

Profile DL2: The beach observed at this point exhibits primarily a widening trend, resulting in a lateral increase of approximately 14.6 meters, except for the upper beach where a slight decrease in elevation of about 0.5 meters was observed. These variations are attributable to the same simultaneous phenomena that impacted the first profile.

Profile DL3: This profile spans a length of 115 meters and has an average slope of approximately 2%. In comparison with the first survey, there is noticeable accretion at the dunes in the upper beach and erosion on the foreshore towards the lower beach over a length of 80 meters.

Profile DL4: This profile extends over a total distance of 95 meters and exhibits a relatively gentle slope in the upper part of the beach, similar to what was observed during the first survey. However, notable variations become apparent as one moves towards the base of the dune and the lower beach. At the base of the dune, a slight decrease in elevation compared to previous measurements can be observed. Conversely, in the lower part of the beach, the profile reveals a lateral gain of approximately 5 meters compared to the previous survey.

Profile DL5: The fifth profile, now measuring 123 meters in length compared to the 111 meters of the first survey, reveals a contrasting evolution compared to the fourth profile. Erosion along the beach due to wind action is observed, accompanied by a lateral gain measuring 12 meters. This variation in coastal morphology between the two profiles highlights the influence of wind-driven processes on the shape of the beach. However, the lateral gain we observed can be directly attributed to sand accumulation impeded by the transverse dike of the fishing port. This infrastructure acts as a barrier that retains sediments, thereby contributing to the change in the shape of the beach.

In general, the topographic profiles along Dalia Beach have revealed a trend of accretion, both laterally and vertically, resulting from the complex interplay between sand movement along the coast and aeolian transport processes. The slight decreases in elevation observed in some profiles, especially in the upper beach area and locally in the intertidal zone, can be directly attributed to the influence of strong winds, particularly the Charqui (eastern) wind, which laterally shifted sand dunes. On the other hand, the lateral gains observed in the eastern part of the beach are primarily due to the effect of the transverse dike of the fishing port, which hindered sand accumulation and contributed to the current configuration of this coastal area.

Ksar Sghir

Six topographic profiles have been conducted along Ksar Sghir Beach, arranged from west to east, as follows:

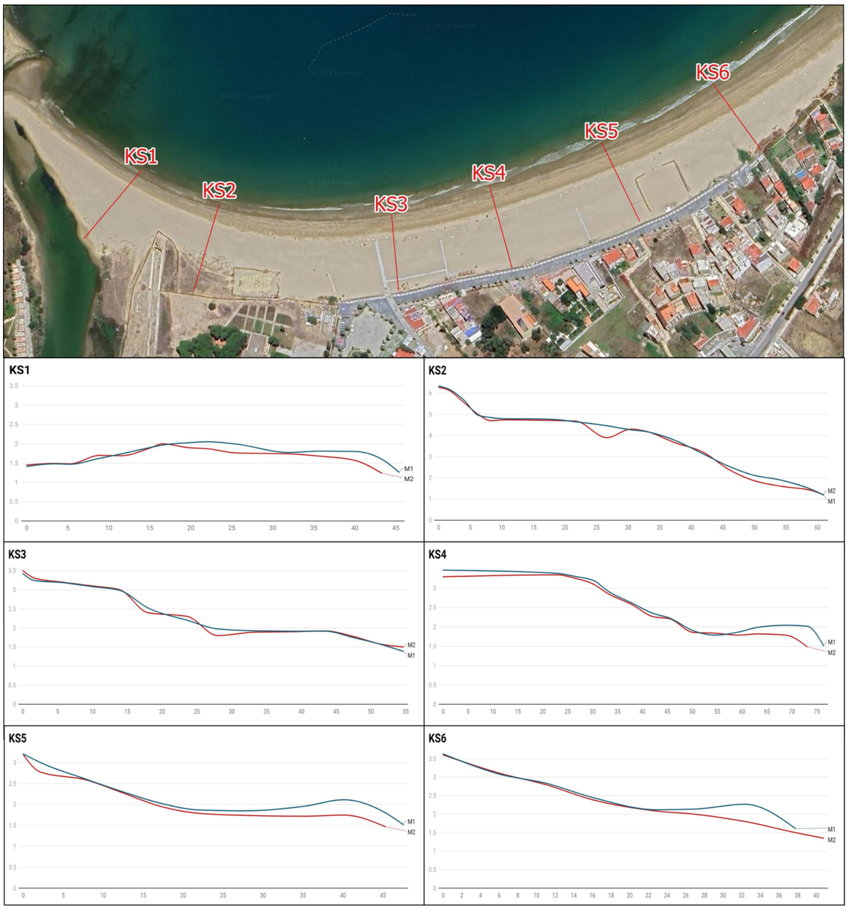

Figure 8: Ksar Shir beach profiles

Profile KS1: located near the mouth of the Ksar Sghir river at the western end of the beach, extends for a maximum length of approximately 43 meters. The profile exhibits an average slope of 2.5% from the upper beach over a distance of 33 meters. This curved morphology may be attributed solely to the reduction in sand deposits carried by the Ksar Sghir River.

Profile KS2: spanning a length of approximately 63 meters, maintains the same geometric shape as the profile from the first mission. The slope exhibits a steep incline of around 18% in the upper beach area, then becomes very gentle over a distance of about 17.5 meters. Subsequently, the slope curvature decreases abruptly to reach approximately 9.7% over a distance of 36 meters towards the underwater beach.

Profile KS3: The coastal fringe at this beach maintains a nearly constant sedimentary balance from the upper beach to the tidal swash zone

Profile KS4: Similarly, profile KS4 did not exhibit significant changes in its overall geometry, except for the distal part of the foreshore. In this area, the sand input has decreased, resulting in a height reduction of approximately 0.5 meters and a lateral retreat of about 3 meters. This has altered the width of the beach at this location, reducing it to approximately 73 meters.

Profile KS5: This profile records a similar geometric evolution to profile KS4. It exhibits a general average slope of 5% over a width of 45 meters, followed by a stable plateau over a distance of 24 meters. In the tidal zone, there is a slight loss of sediments in both horizontal and vertical directions. This evolution could be attributed to the action of wind.

Profile KS6: At the eastern end, the profile is stable. Compared to mission 1, fluctuations are recorded at the bottom of the beach, with a loss in altitude and a lateral gain of about 3 meters.

The general appearance of all the profiles surveyed, compared to the profiles from the first mission, does not show major changes, especially concerning the width. However, one can observe slope breaks and a decrease in heights. This evolution can be attributed to several factors, including variations in weather conditions during the profile surveys carried out during both missions and the reduction in sediment inputs carried by the river. These temporary variations are the result of natural processes resulting from the combined interaction of river and wind forces.

Discussion

Several key factors, including existing marine currents, seafloor characteristics, coastal morphology, and the depth of the coastal platform influence the dynamics of the coastline and sediment transport. These factors play a crucial role in shaping the distinct physiographic systems of Moroccan beaches along the Strait. Positioned between capes and supplied by sediment transport from adjacent wadis, such as the Tizérène formations, beaches like Dalia exhibit unique sand typologies with fine grains and suspended clay particles.

In the majority of the coastal area under study, the seabed is composed of bedrock. This means that, although the port could theoretically influence sediment transport in the region, this does not occur in reality. There is a limited amount of sediment available for transport, and the presence of a hard seabed and significant depths reached over a short distance create a natural barrier to sediment transport.

An analysis of the current direction suggests that any potential impact would be manifested in a northward direction. Hypothetically, the only area that could be affected by new sediments is the Dalia beach.

Monitoring of shoreline kinematics and topographic monitoring has shown no sedimentary deposits at Dalia Beach, for the following reasons:

- Specific coastal configuration: The current configuration of the beach is influenced by Cap Cires, which acts as a barrier to strong marine currents;
- Limited amount of transportable sediment: The presence of hard bottoms limits the amount of sediment that can be transported;
- High depths: The water depth increases rapidly before reaching the beach, making it difficult for sediments to reach the shore.

The sedimentary dynamic at Ksar Sghir Beach is profoundly shaped by the combined effects of marine hydrodynamics and riverine contributions. The intricate interplay between these marine and fluvial processes plays a pivotal role in the establishment and progression of the coastal system. This dynamic interaction significantly influences the sedimentary dynamics, ultimately contributing to the unique character and evolution of Ksar Sghir Beach.

Conclusion

Investigating the potential influence of the Tangier Med port complex and associated offshore dredging on the coastal dynamics of Dalia and Ksar Sghir beaches, this study employed a comprehensive, multi-methodological approach. The analysis aimed to gain a holistic understanding of the coastline's evolution and potential anthropogenic impacts.

Firstly, historical shoreline tracking techniques were employed, leveraging a multi-decadal archive of aerial photographs and satellite imagery (1988-2022). Utilizing the Digital Shoreline Analysis System (DSAS), a rigorous quantitative and visual assessment of shoreline change was undertaken. This analysis revealed a consistent trend of coastal erosion throughout the timeframe. Notably, the erosion rate during the pre-construction period (1988-2004) exceeded that observed subsequently. This intriguing observation warrants further investigation and suggests a potential stabilizing effect associated with the port complex and dredging activities, potentially mitigating the impact of natural factors such as frequent storms and disruptive waves.

To further substantiate these findings, detailed topographical surveys were conducted in 2012 and 2022. These surveys revealed overall coastal profile stability, with minor fluctuations attributable to meteorological and riverine influences. This corroborates the findings from the shoreline analysis, providing additional empirical evidence for the potential stabilizing effect of the port complex and dredging.

In conclusion, this study reveals a complex interplay between anthropogenic alterations and natural forces in shaping the coastal evolution of Dalia and Ksar Sghir. While the Tangier Med port complex and associated dredging may have contributed to shoreline stabilization, the impact of natural events during the pre-construction period should not be disregarded. This research highlights the multifaceted dynamics of coastal environments and underscores the critical importance of considering both natural and anthropogenic factors in coastal management and planning.

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