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Diachronic Study of the North Atlantic Coast of Morocco between Larache and Moulay Bousselham – A Geometric Approach

Soukaina El Idrissi[1*], Oumaima Zerdeb[1], Allal Labriki[2], Sakina Mehdioui[1], Mariyam El Omari[1], Saïd Chakiri[1], Sultana Inekach[3]

[1] Geosciences Laboratory, Faculty of Sciences, Ibn Tofail University, Kenitra, Morocco

[2] Laboratory of Geosciences and Applications, Faculty of Sciences Ben M'Sik, University Hassan II of Casablanca, B.P.7955, Casablanca, Morocco

[3] Natural Resources and Sustainable Development Laboratory, Faculty of Sciences, Ibn Tofail University, Kenitra, Morocco

* Corresponding author's e-mail: soukaina.elidrissi1@uit.ac.ma

ABSTRACT

Coastal areas, vital for local communities, are subject to significant changes requiring rigorous management. This study focused on assessing the evolution of the Atlantic coastline between Larache and Moulay Bousselham over a period of 60 years, with an emphasis on erosion and accretion risks. The main objective was to understand coastal change trends and identify the most vulnerable areas. Using advanced techniques such as multi-temporal photo interpretation, geographic information system (GIS), and the digital shoreline analysis system (DSAS), the aerial and satellite images from 1963, 1991, 2014, and 2023 were analyzed. The results reveal that zones A (Msitro Beach) and B (Lhayayda Beach) are primarily affected by erosion, with minimal accretion, while zones C (Mersat lghnem beach) and D (Moulay Bousselham Beach) exhibit more intense erosion. This study provides an original contribution by combining advanced analytical methods to inform on the sustainable management of coastal resources.

Keywords: Atlantic coastline, erosion, accretion, DSAS, GIS.

INTRODUCTION

Morocco boasts an extensive coastline stretching nearly 3,500 km, bordering both the Atlantic Ocean and the Mediterranean Sea. This Moroccan coastline serves as a convergence point for economic pressures and demographic growth, where land competition is particularly intense (Hilal, 2016) and (El Arrim, 2001). Coastal erosion is a global phenomenon affecting numerous coastal regions worldwide. In the current context of climate change and sea-level rise, this phenomenon tends to worsen and has increasingly severe consequences on coastal ecosystems, local communities, and infrastructure. Consequently, any alteration to this coastline could have significant repercussions on the economy and local biodiversity of the country, in addition to the well-being of coastal populations. Population growth and increasing urbanization along the Moroccan coastline intensify land pressures and exacerbate usage conflicts among various stakeholders (farmers, fishermen, real estate developers, etc.). In this context, understanding coastal erosion and accretion processes becomes essential for sustainable and balanced coastal management.

The consequences of coastal erosion in Morocco are manifold, including the loss of arable land, deterioration of natural habitats, and endangering coastal communities, making this issue particularly relevant for the country's sustainable development (Azidane, 2019). Within the framework of tourism development along the coast, it is imperative to consider these aspects. The objective of this article was to assess the coastal movements from Larache to Moulay Bousselham over a 60 – year period. This extended study duration will allow for a more in-depth analysis of coastline movement and identification of long-term trends, which is essential for understanding the evolution of coastal erosion and its long-term implications for sustainable development and coastal tourism. It relies on photo-interpretation (from aerial photographs and satellite images) as well as the implementation of a geographic information system (GIS) associated with a digital shoreline analysis system (DSAS), all supported by field observations and surveys.

Presentation of the study area

The coastline stretching from Larache to Moulay Bousselham is a coastal area located in the northwest of Morocco, along the Atlantic coast, between the Rabat-Salé-Kénitra region to the south and the Tanger-Tétouan-Al Hoceima region to the northeast (Figure 1). The studied coastline is characterized by diverse environments and morphological units, including sandy beaches, lagoons, estuaries, cliffs, marshes, and more.

The Lower Loukkos complex or Larache marshes consist of a variety of environments, including an estuarine area, shallow waters along the seashore, salt meadows, freshwater ponds, floodplains, and several abandoned salt pans. The estuary of the Loukkos River extends to the guard dam erected to prevent the tide from reaching agricultural lands (Laouina, 2010) and (Chahid, 2022). The estuarine area of the Loukkos River and the former salt pans extend upstream, near the lower course of the Loukkos, including the reservoir formed by the guard dam. This area encompasses extensive marshlands densely vegetated along the valley, primarily fed by the Loukkos' tributaries (Laouina, 2010).

The Merja Zerga lagoon undoubtedly represents the most significant coastal wetland in Morocco, hosting remarkable biodiversity and internationally valuable avifauna (Laouina, 2010). The Atlantic coastal region from Larache to Moulay Bousselham generally experiences a temperate Mediterranean climate (El Habti et al., 2022b) (Figure 2). Summers are often hot and dry, while winters tend to be mild and humid. Precipitation is more frequent during the winter season, whereas summers are generally dry. However, due to the oceanic influence, temperatures can be moderated by the proximity of the sea, creating a slightly cooler coastal climate compared to inland regions.

MATERIALS AND METHODS

The methodology used in this study relies on proven techniques of digital geographic information processing, widely employed in the field of coastal dynamics. This methodological approach enabled to extract reference lines from selected documents for observation, thereby facilitating the spatiotemporal analysis of coastal zone evolution at a local level (e.g., Aangri, 2022). The analytical method adopted in this research focused

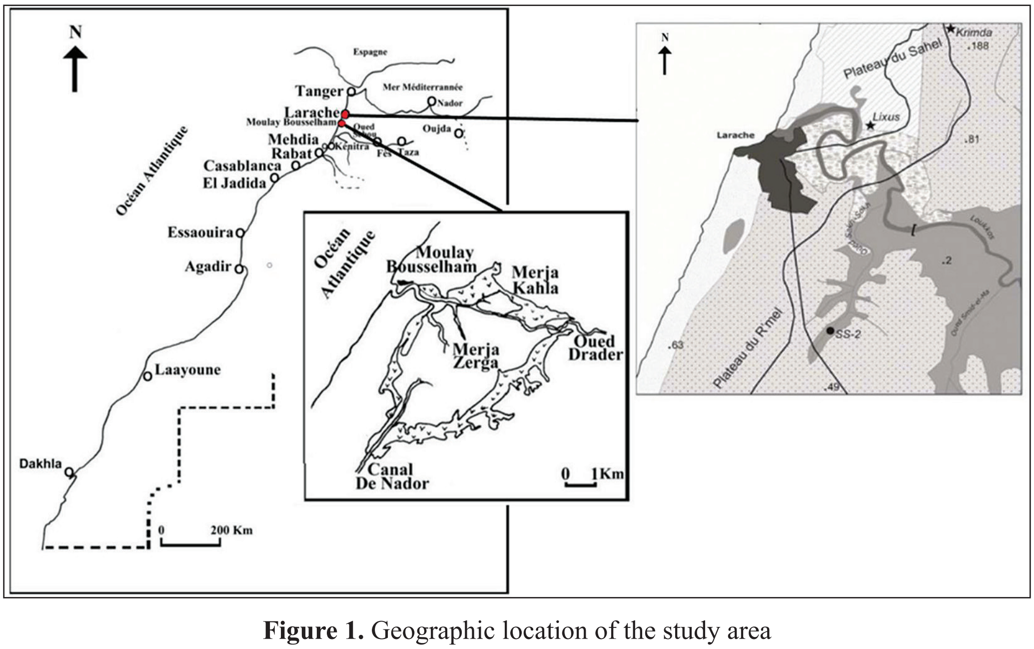


Figure 1. Geographic location of the study area

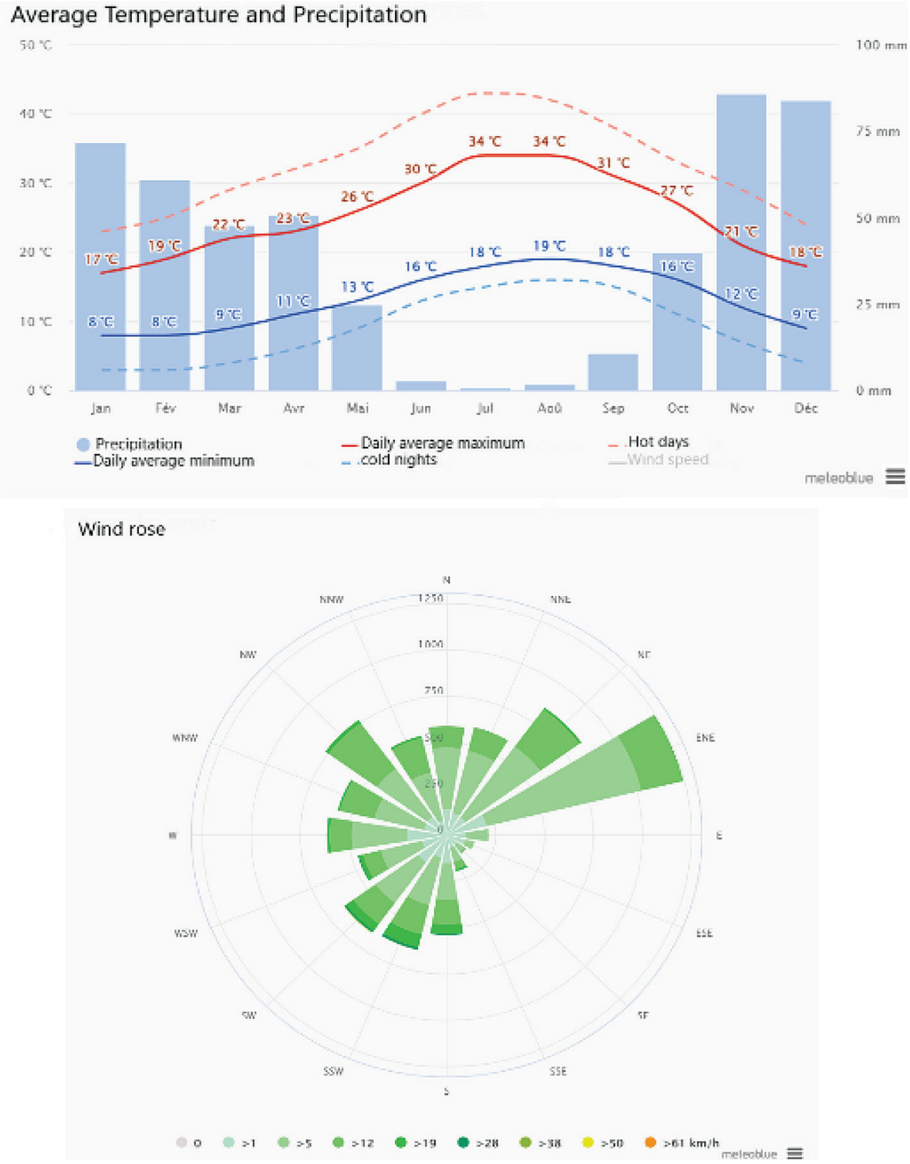


Figure 2. Climatic data of the study area

on photo-interpretation to assess changes in the coastline. The operational approach, based on available data, followed these steps: selection of a reference line suitable for the study area and the types of documents used, geometric correction of the data, and extraction of reference lines representing the coastal position (Moussaid, 2015).

Basic data

Aerial photographs

To study the dynamics of the coastline, an analysis through photo-interpretation was conducted using three series of aerial photographs from 1963, 1991, and 2014, as well as a satellite image from 2023. This observation spans a period of 60 years (as indicated in the Table 1). The data scales range from 1/20,000 to 1/40,000, while the 2023 satellite image stands out due to its high resolution of 100 meters. These specific years were chosen due to the availability of reliable historical data for these periods and their relevance to the study of the long-term evolution of the coastline in the study region. Additionally, the inclusion of a recent satellite image from 2023 allows for a more precise and current comparison of the coastline dynamics (Appeaningaddo et al., 2008).

Topographic maps

In order to perform geometric correction of the aerial photographs, four topographic maps of Moulay Bousselham, Lalla Mimouna, Sidi Allal

Table 1. Data from aerial missions in the years 1963, 1991, and 2014, and from the 2023 satellite image

Year	Document type	Scale	Nature	Number of Aerial Photographs Used	Source
1963	Aerial Photos	-	Black and White	8	L'ANCFCC
1991	Aerial Photos	1/40000	Black and White	7	L'ANCFCC
2014	Aerial Photos	1/20000	Color	14	L'ANCFCC
2023	Satellite Image	-	Color	4	(Terraincognita)

Tazi, and Larache at a scale of 1/50,000 were utilized (Table 2).

Software and tools used

During the study, the following tools were utilized:

- ArcGIS 10.5: this GIS and mapping software, along with its various extensions, was used for final data processing and the production of thematic maps (Rabii, 2017).
- DSAS v5.0: developed by the United States Geological Survey, the "Digital Shoreline Analysis System" is a GIS application for ArcGIS 10.5 that facilitated statistical calculations on transects perpendicular to the coastline, providing evolution rates based on observed differences (Salim, 2018).
- Terra Incognita: this software offers a simple and practical solution with high spatial resolution. It can be downloaded as a reference for various types of maps, such as Google Maps, Bing, OpenStreetMap, etc.

Methodology for studying coastline dynamics

The management and preservation of coastal areas are challenging due to their intrinsic complexity. These areas require updated and quality information to facilitate informed decision-making. This necessity gives particular importance to information management for decisions concerning coastal areas (Nakhli, Ghazi, 2008).

GIS are part of a set of approaches, methods, and tools grouped under the generic term "Geomatics." While the interest in GIS for coastal environments has been recognized for several decades, it was only in the early 1990s that their applications began to diversify and multiply (Gourmelon, Robin, 2005).

Digitization of aerial photographs and topographic maps

The digitization of cartographic data and aerial photographs constitutes the initial phase (El Khalidi, 2012), focusing on digitizing aerial photographs and topographic maps to obtain digital data from paper documents. A set of four topographic maps and 33 aerial photos was utilized, all digitized at a resolution of 600 dpi, ensuring a pixel size of approximately 1×1 meter for these images. This spatial resolution of the documents used enables a reliable estimation of coastline mobility over 60 years.

Georeferencing of topographic maps and geometric rectification of aerial photos

To align and correct distortions in the aerial photos concerning the topographic maps, the georeferencing process was implemented within a well-defined projection system (North Morocco degree) using ArcGIS 10.5 software. This involved identifying precise ground control points (roads, buildings, salt marshes, etc.) to calibrate the images. The aerial photos from 1963, 1991, 2014, and 2023 were georeferenced using the topographic maps as a base.

Geometric rectification of the aerial images was performed using a polynomial method suited for relatively flat terrains, employing 16 to 30 tie

Table 2. Characteristics of the topographic maps

Topographic maps	Year	Scale	Nature	Source
Moulay Bousselham	2000	1/50000	Color	L'ANCFCC (National Agency for Cadastre, Land Registry, and Cartography
Lala mimouna	1996	1/50000	Color	L'ANCFCC
Sidi allal tazi	1974	1/50000	Color	L'ANCFCC
Larache	1990	1/50000	Color	L'ANCFCC

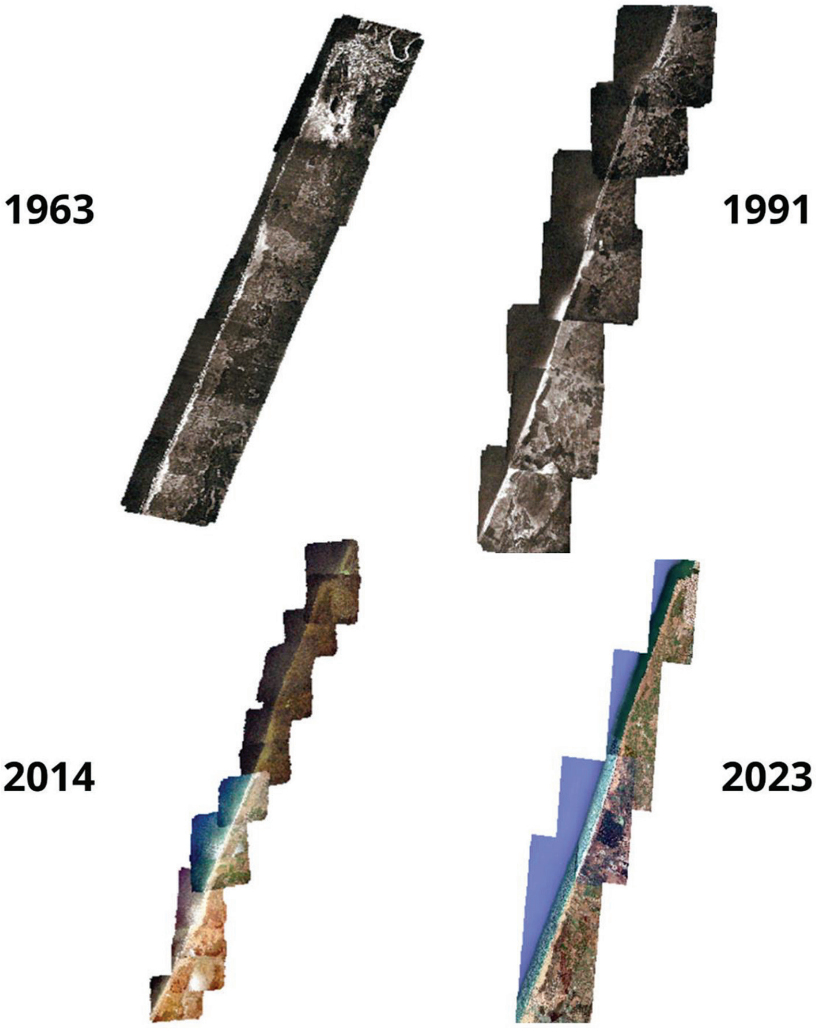


Figure 3. Mosaic of aerial photos from 1963, 1991, 2014, and the 2023 image

points per image to minimize root mean square error. This rectification occurred in two phases: first, the recent images were rectified to create a base reference, and then the older images were aligned to the rectified recent images.

Mosaicking of aerial photos

The creation of mosaics from georeferenced images was carried out for each flight plan (Salim, 2021). This process involved eliminating the image edges, reducing overlapping areas, and processing these areas to ensure consistency and color homogeneity across the entire study area.Figure 3 illustrates the mosaic of the georeferenced images.

Assessment of uncertainties and errors affecting the reference lines

On the basis of previous studies (Thieler., Danforth,1994), (Moore, 2000), and (MORTON et al,2004), various errors were estimated, including digitization error, Root Mean Squared Error (RMSE), pixel error, and variations in the position of the oscillation line induced by the high tide level. These errors are combined according to equation (1) to obtain an overall estimate of the coastal position error, expressed by the term ‘Esp’.

$$Esp = \sqrt{Ed^2 + ERMSE^2 + Ep^2 + Ev^2} \quad (1)$$

where: *Esp* – coastal position error, *Ed* – digitization error, *ERMSE* – errors related to image rectification, *Ep* – pixel error, *Ev* – variations in the position of the oscillation line induced by high tide level.

Using this formula, a maximum annualized error for the study area over a period of 60 years was assessed at ± 0.66 m/year. This evaluation is based on uncertainty analysis for each period and each coastal segment. Additionally, specific errors were identified. For instance, the precision of landmarks (reference points) on the 1/50000 map was estimated at ± 10 meters, representing a source of systematic error. However, this uncertainty does not impact the evolution of the coastline between two photographs. Regarding the aerial photographs, uncertainties may arise when the coastline is not clearly visible, often associated with slight blurriness. For these images, the Root Mean Squared Errors (errors related to image rectification) for each image were lower than or equal to 0.5 meters (Table 3). By combining the errors related to measurement precision, coastline detection method, and georeferencing, the overall accuracy of the coastline detection method was estimated at ± 4 meters. This uncertainty analysis helps in understanding the limitations and reliability of the results obtained when studying coastline evolution from iconographic documents (Table 4).

Coastal change measurement method and statistical analysis

In this study, the choice of the adopted technique takes various elements into account (8). Typically, this choice should consider the data used, the selection of the coastline, and the level of precision required to conduct this study (Moore, 2000) and (Boak, Turner, 2005). For this specific research, the assessment of linear changes was automated using the DSAS integrated into the GIS. This software, developed by the US Geological Survey (Thieler et al, 2009), enabled the tracking of transects perpendicular to the coastlines for comparison. Thus, the DSAS program generated 774 transects perpendicular to the baseline, spaced 50 meters apart and extending over a length of 4000 meters, thus providing complete coverage of the coast. These transects, numbered from North to South, were created to finely capture the evolution of coastline across the entire study area (Fig. 4).

After the creation of these orthogonal transects, DSAS calculated the rate of coastline change along each of them for each period using three methods. Firstly, the End Point Rate (EPR), which is the simplest method, evaluates the rate of change by considering the distance covered by the shore divided by the time between the oldest and most recent shoreline (Thieler et al, 2009). Secondly, the Least Squares Linear Regression (LRR) method that fits through all intersections of historic coastline lines on a transect, where its slope represents the annual rate of shoreline change in meters per year (Himmelstoss et al, 2018). Finally, the Weighted Linear Regression (WLR) method, which assigns weight to each value of measured

Table 3. Root mean squared errors (RMS) related to image rectification

Year	Number of tie points	RMS error (m)
1963	24	0.567
1991	18	0.118
2014	30	0.49
2023	16	0.107
Average		0.32

Table 4. Estimated annualized maximum error

Error category	Estimated value
Errors in determining reference points	±10
Measurement errors on corrected aerial photographs	± 1
Annualized transect error (m/year) Eα	± 0.66

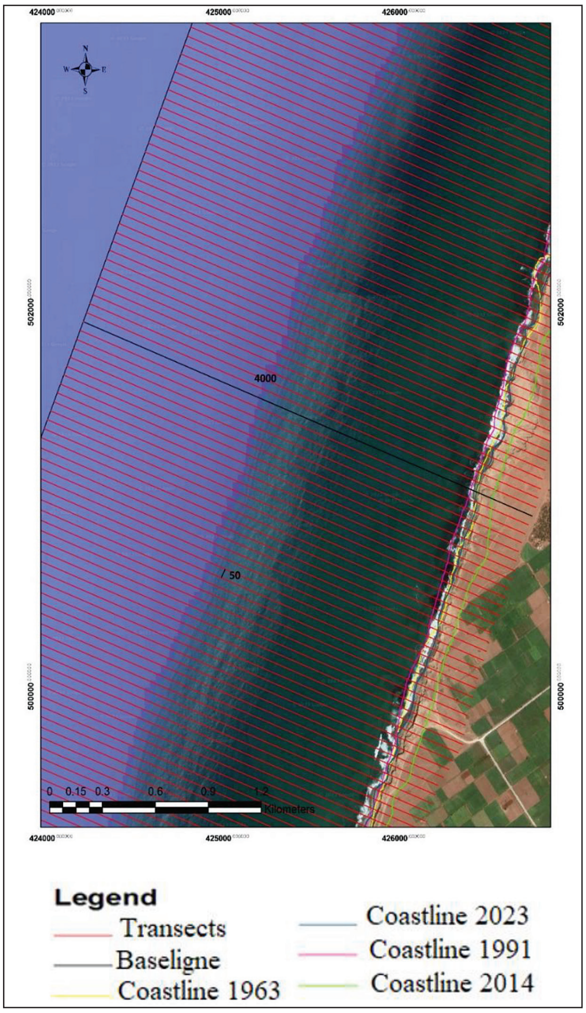


Figure 4. Generation of transects by DSAS and input parameters (Baseline and Coastline)

differences between shoreline positions over time, requiring a minimum of three historical shoreline positions to calculate the rate of change (Genz et al, 2007) and (Himmelstoss et al, 2018).

RESULTS AND DISCUSSION

The conducted study synthesizes the coastal changes along the Larache to Moulay Bousselham coastline since the 20th century, covering approximately 44 kilometers of shoreline. Initially, the various positions of the selected reference lines were compared to understand the temporal evolutions of coastal dynamics (Figure 5).

Examining interpretations of aerial images from 1963, 1991, 2014, and 2023 provided crucial insights into understanding the evolution of the shoreline over a 60-year period. Variations in the position of the coastline between 1963 and 2023 demonstrate a progressive trend along the studied 44 km of coastline. On the basis of this information, the end point rate (EPR) is a measure representing the distance between the oldest and most recent shoreline, divided by the time period between these two points. This value is expressed in meters per year and is depicted in the graph (Figure 5) and table (Table 5) under the heading annual average. The study area was divided into four sectors from North to South.

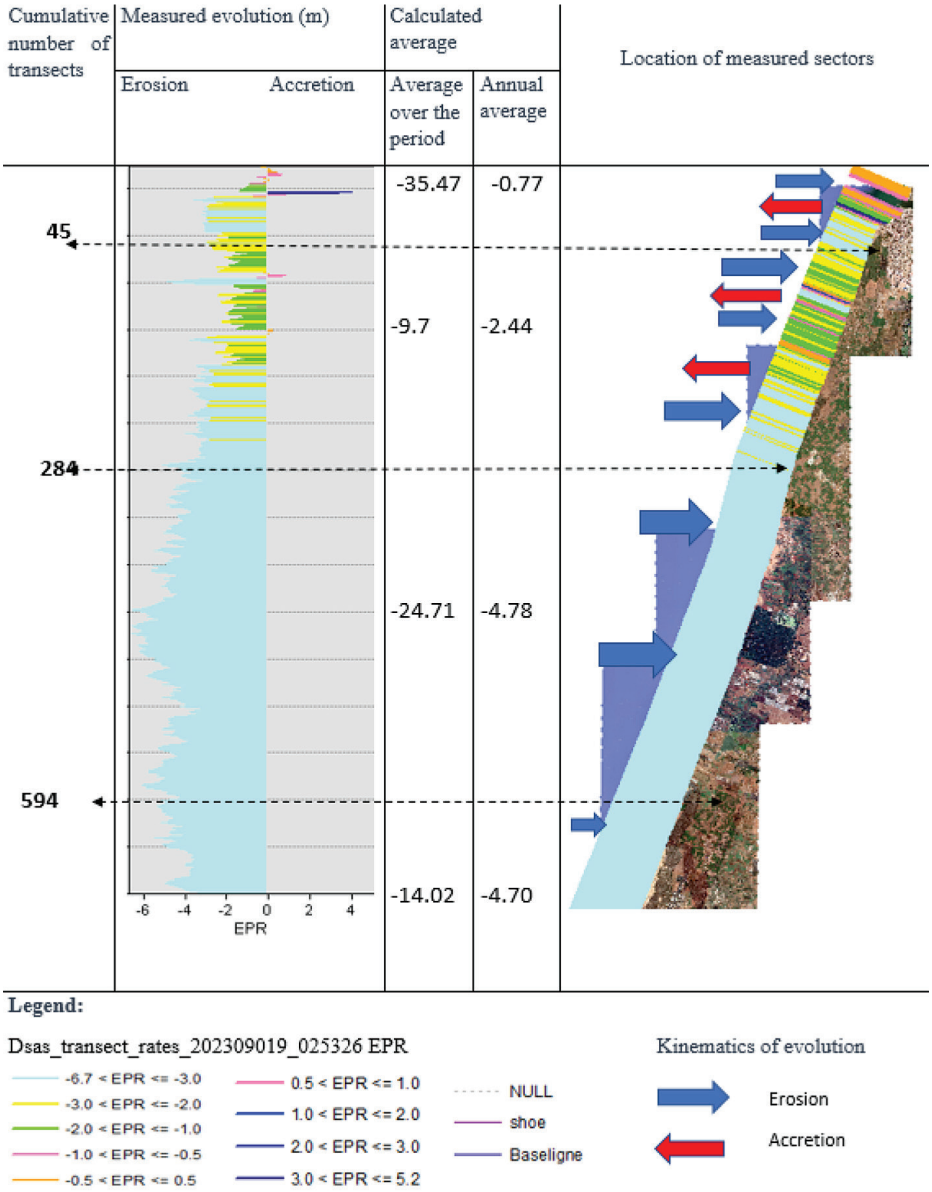


Figure 5. Map-based model utilizing linear regression calculation (EPR) between two dates 1963–2023, (erosion and accretion)

Table 5. Statistical calculation of the EPR index for the variation of the high tide line from 1963 to 2023 along the Larache to Moulay Bousselham coastline

Study sectors		Msitro beach	Lhayayda beach	Mersat Ighnem beach	Moulay Bousselham beach
Number of transects		45	239	310	180
Length (km)		3.4	6.17	4.6	5.68
EPR	Average coastal mobility (m/year)	-0.77	-2.44	-4.78	-4.70
	Minimum coastal mobility (m/year)	-3.81	-5.21	-6.7	-3.43
	Maximum coastal mobility (m/year)	5.17	1.29	-2.88	-6.09
	Total number of transects showing erosion	30	234	310	180
	Total number of transects showing accretion	13	5	0	0

Sector A: Msitro Beach

This coastal segment, located to the north of the study area, extends over approximately 3.4 km and is divided into 45 transects numbered from 1 to 45 (Figure 6). An alternation between areas experiencing erosion and those showing accretion is observed. Out of the 45 transects studied along this beach, 30 exhibit erosion while 13 show accretion. The average retreat rate is -0.77 m/year, with extreme values ranging from a maximum retreat of 5.17 m/year to a minimum retreat of -3.81 m/year.

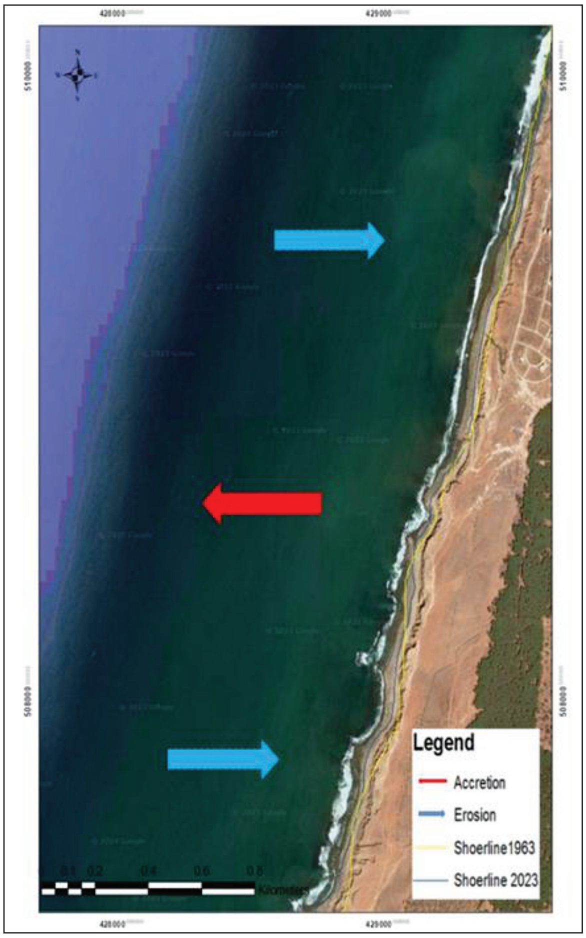


Figure 6. Areas of erosion and accretion along Msitro Beach (Sector A)

Sector B: Lhayayda Beach

Lhayayda Beach comprises 46 to 285 transects, covering a shoreline stretch of 6.17 km. Here, a pattern of both accretion and erosion zones is observed. The average retreat rate is -2.44 m/year, with a maximum of -5.21 m/year and a minimum of 1.29 m/year. Spatial-temporal analysis of the shoreline has revealed significant variations. It is worth noting that these results might be slightly influenced by a margin of error of ±0.66 m, especially in the areas with minimal changes (Figure 7).

Sector C: Mersat Lghnem Beach

In Sector C, consisting of 310 transects, the figure below (Fig. 8) illustrates the evolution of the shoreline at 'Mersat Lghnem Beach' from 1963 to 2023, covering a stretch of 4.6 km. This representation demonstrates significant erosion characterized by a pronounced retreat of the coastline. The intensity of this erosion gradually increases moving southward. The average rate of retreat is estimated at -4.78 m/year, with a maximum of -2.88 m/year and a minimum of -6.7 m/year.

Sector D: Moulay Bousselham Beach

This sector, situated to the south of the studied coastal area, covers approximately 5.68 km (Fig. 9). It exhibits significant coastal erosion

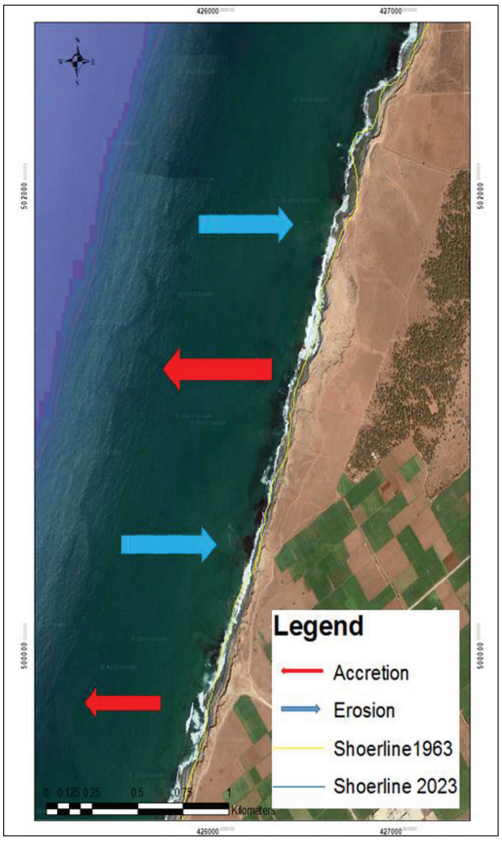


Figure 7. Alternation between accretion and erosion zones along Lhayayda Beach

observed across all 180 analyzed transects, accounting for 100% of transects showing erosion. The average loss of the coastline is estimated at -14.02 m, corresponding to an average retreat rate of -4.70 m/year, with a maximum of -6.09 m/year and a minimum of -3.43 m/year.

Coastal evolution from Larache to Moulay Bousselham from 1993 to 2023:

- phase 1963–1991: Over a coastal stretch of 36.71 km studied over 28 years, the average retreat of the coasts was assessed at over 2.42 meters. Cinematic analysis revealed an alternation between areas of accretion and others in erosion. Of the 770 transects studied, 725 showed erosion (94.1%), while 45 showed accretion (5.8%).
- phase 1991–2014: Over a period of 23 years, examination of the high tide lines revealed an alternation between erosion and accretion along the 36.71 km of studied coastline. Among the 781 transects analyzed, 766 demonstrated erosion (98.01%), while only 15 indicated accretion (1.92%).
- phase 2014–2023: Over a period of 9 years, the evolution of the high tide line oscillated between phases of erosion and progradation

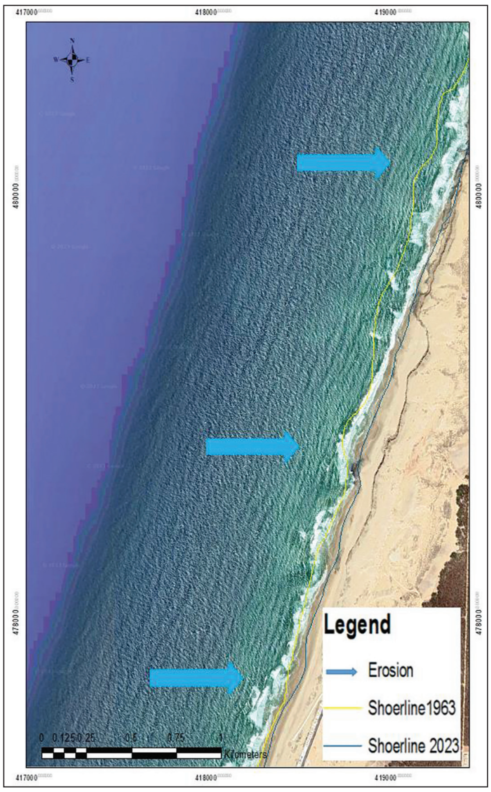


Figure 8. Significant erosion marked by a pronounced retreat of the coastline at Mersat Lghnem Beach (Sector C) moving southward

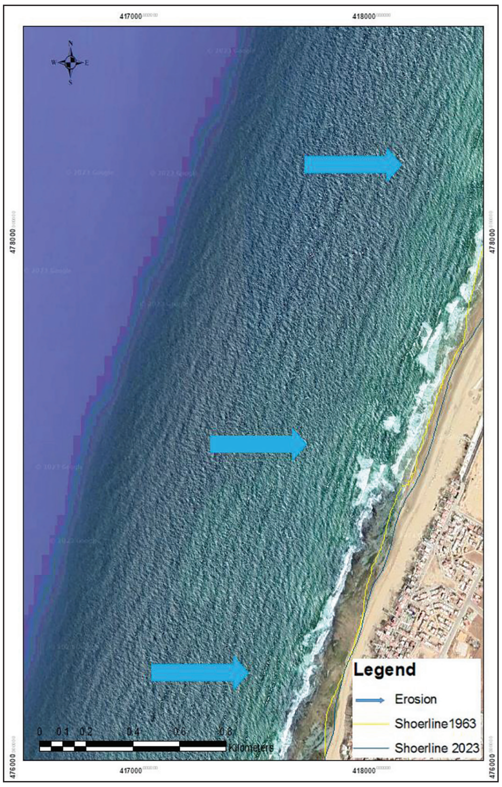


Figure 9. Significant coastal erosion observed across all analyzed transects in Moulay Bousselham Beach (Sector D)

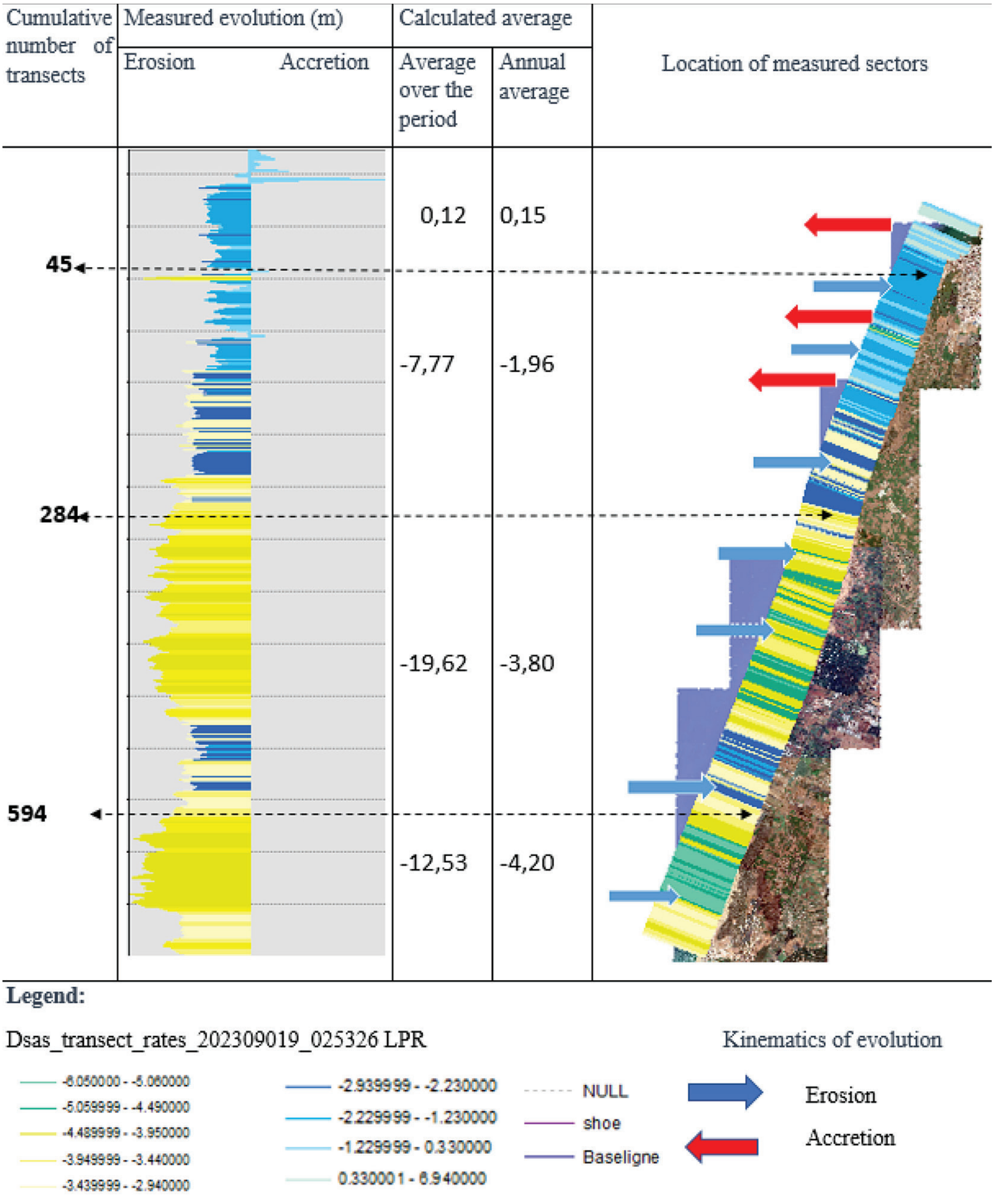


Figure 10. The cartographic model based on linear regression calculation (LRR) between two dates 1963–2023 (erosion and accretion**)**

along the 36.71 km of coastline examined. Among the 777 transects studied, 467 showed progradation (60.1%), while 310 presented erosion (39.9%).

The results of the diachronic analysis of the coastline, conducted using the automated thresholding methods LRR (Linear Regression-based method) and WLR (Windowed Linear Regression), are presented in Table 6, as well as in Figures 10 and 11. The selection of DSAS statistical parameters in this study was crucial for exploring the temporal and spatial dynamics of coastal changes, as well as the geomorphic variability

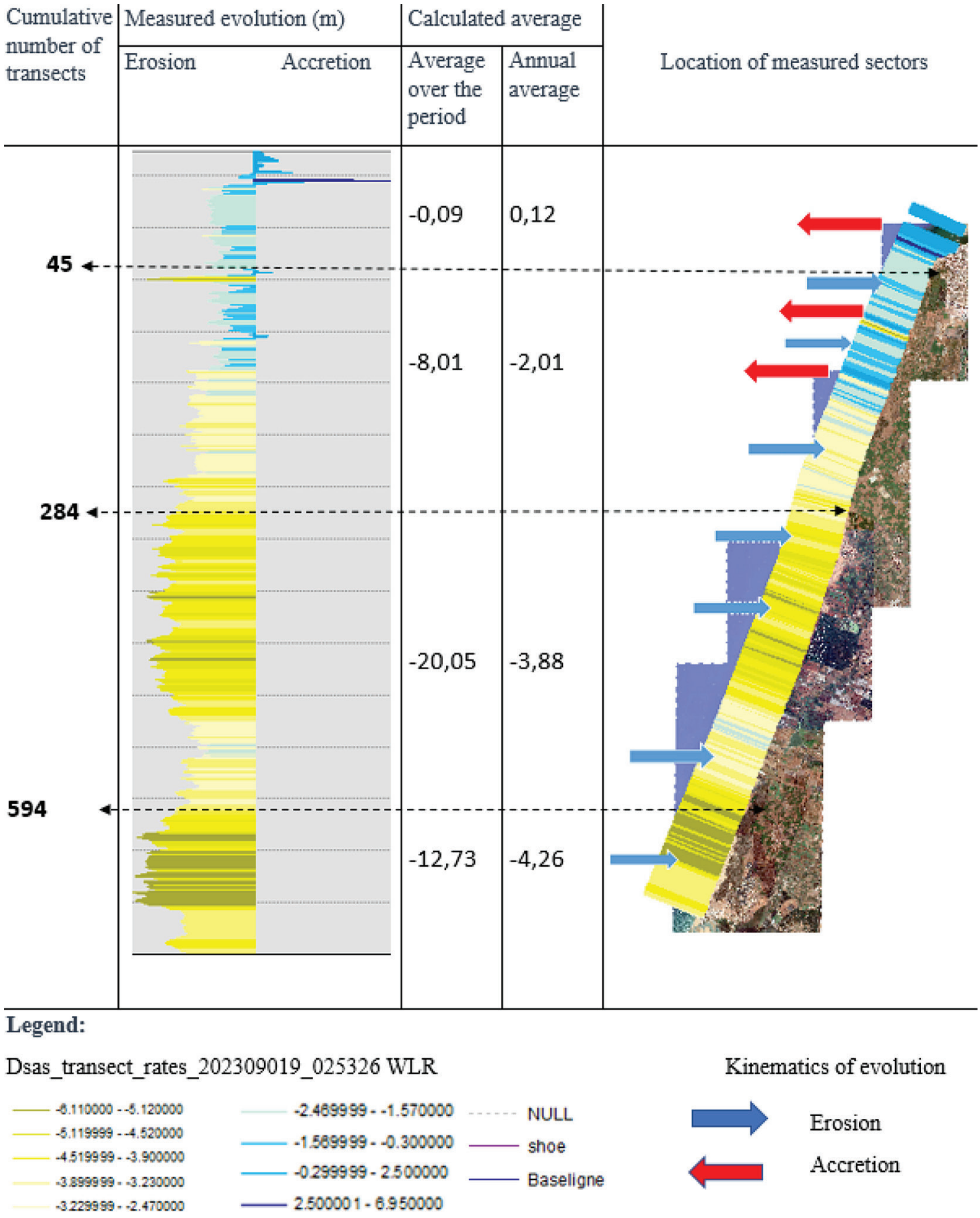


Figure 11. The cartographic model based on windowed linear regression (WLR) calculation between two dates 1963–2023 (erosion and accretion)

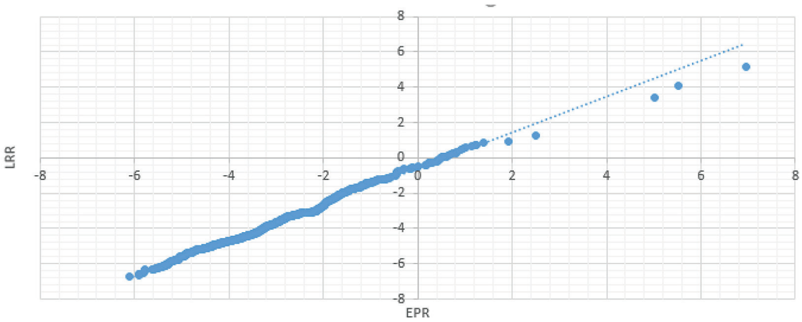
along the beach. These parameters were chosen for their ability to integrate all shoreline positions, assess cumulative shoreline movement, and consider the temporal dimension, allowing for an in-depth analysis of coastal dynamics. The rates of change calculated by EPR, LRR, and WLR were compared to determine the best method:

- EPR/LRR: Upon analysis of the table, it appears that the mean, maximum, and minimum shoreline mobility values from EPR are lower than those from LRR. The measurements of the EPR index between the shorelines show an erosive dominance compared to LRR (Fig. 12).

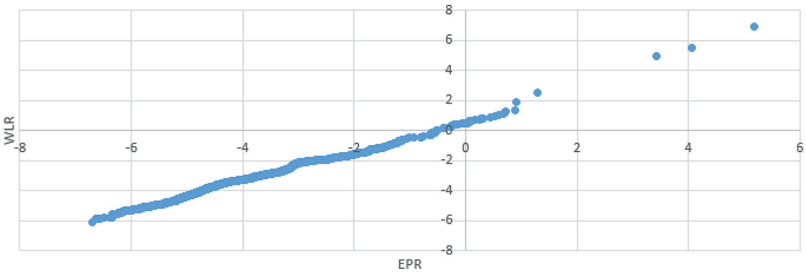
Table 6. LRR and WLR Statistics between 1963 and 2023

Sectors of study		Plage Msitro	Plage Ihayayda	Mersat Ighnem beach	Plage Moulay Bousselham
Number of transects		43	239	310	180
LRR	Average coastal mobility (m/year)	0.15	-1.96	-3.80	-4.20
	Minimum coastal mobility (m/year)	6.95	0.95	-1.82	-2.49
	Maximum coastal mobility (m/year)	-2.45	-5.25	-5.20	-6.05
	Total number of transects showing erosion	18	232	310	180
	Total number of transects showing accretion	27	7	0	0
WLR	Average coastal mobility (m/year)	0.12	-2.01	-3.88	-4.26
	Minimum coastal mobility (m/year)	6.94	0.92	1.9	-2.57
	Maximum coastal mobility (m/year)	-2.52	-5.29	-5.36	-6.11
	Total number of transects showing erosion	18	720	310	180
	Total number of transects showing accretion	27	7	0	0

EPR/LRR



WLR/EPR



LRR/WLR

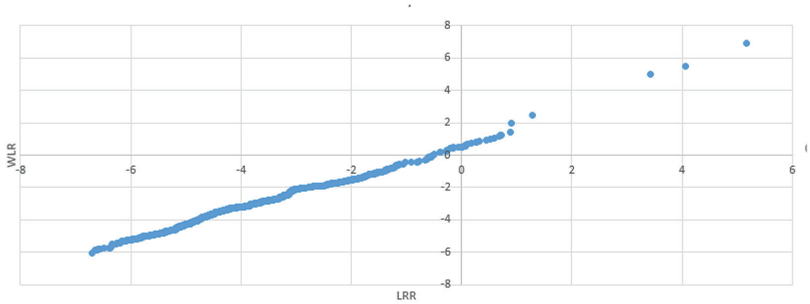


Figure 12. Comparison of the evolution rates calculated by EPR, LRR, and WLR

- WLR/EPR: Upon examination of the table, the mean, maximum, and minimum shoreline mobility values from WLR are higher than those from EPR. The number of transects recorded in accretion for the WLR index is higher than that for EPR.
- WLR/LRR: The measurements from both indices yield almost identical results.

When comparing these results, it appears that the most reliable method is linear regression, as it enables an appreciation of the trend across all the studied periods.

CONCLUSIONS

In the context of this study, aimed at assessing the evolution of the Atlantic coastline between Larache and Moulay Bousselham over a 60-year period, the results highlight significant coastal change trends. The use of advanced techniques such as multi-temporal photo interpretation, GIS, and the DSAS enabled the analysis and quantification of erosion and accretion risks in the study area. The results reveal that the beach undergoing the most intense erosion is Moulay Bousselham Beach, with an average erosion rate estimated at approximately -4.20 m/year. In comparison, Mersat lghnem and Lhayayda beaches exhibit slightly lower erosion rates, with respective values of -3.80 m/year and -1.96 m/year. The calculated average erosion rate for these beaches underscores the importance of coastal management interventions to prevent potential damage to the environment and local communities. These findings are crucial for identifying the most vulnerable areas of the Atlantic coastline from Larache to Moulay Bousselham and guiding sustainable coastal resource management strategies in this region. It appears that Moulay Bousselham Beach is the most vulnerable, followed by Mersat lghnem and Lhayayda beaches, due to their higher erosion rates. By combining advanced analytical methods, this study makes a significant contribution to understanding the evolution of the Moroccan Atlantic coastline and implementing tailored measures to preserve these coastal areas vital for local communities.

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