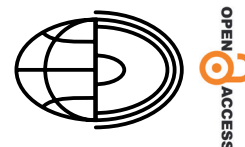


Algerian shoreline changes (1986–2024) monitored and assessed using remote sensing and GIS techniques



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Abstract. This paper assesses diachronic shoreline dynamics in Algeria. To achieve this, remote sensing and Geographic Information System (GIS) techniques were employed to analyse shoreline changes over the 38-year period from 1986 to 2024. Landsat mission satellite images were processed and analysed to extract the shoreline. Following verification and validation of the extracted shorelines, their evolution parameters were calculated using the Digital Shoreline Analysis System (DSAS). Net Shoreline Movement (NSM), End Point Rate (EPR) and Linear Regression Rate (LRR) were then used to quantify erosion and accretion rates along the Algerian shoreline. The most recent Algerian shoreline extraction revealed an estimated total length of 1,683.88 km. Significant changes to the Algerian shoreline were identified: accelerated erosion between 1986 and 2000; a stabilising trend between 2000 and 2014; and general accretion during the period 2014–2024. However, this long-term analysis (1986–2024) highlights significant heterogeneity in Algerian coastal dynamics, with a net trend towards coastal erosion. Indeed, 55.4% of the shoreline has eroded, 16.64% has been stable, and 27.96% has accreted. Furthermore, the average NSM was estimated to be approximately –7.6 m, indicating moderate shoreline retreat. The EPR and LRR values were –0.201 m/year and –0.218 m/year, respectively, confirming an overall trend towards coastal erosion.

Key words:
Shoreline change,
GIS and Remote Sensing,
MNDWI,
Landsat,
Algeria

Introduction

Coastal zones constitute dynamic yet fragile environments that are constantly influenced by multiple natural factors such as wind, waves, currents, and sediment transport (Paskoff 1992; Pinot 1998; Wright et al. 2019). Other anthropogenic factors, such as the

construction of dams, harbours and coastal defence structures, as well as urbanisation and sand mining, can alter coastal dynamics (Paskoff 1993; Scott 2005). Coastal erosion is one of the major environmental issues facing the world's shorelines and is linked to climate change and anthropogenic pressures (Łabuz 2015). In fact, 70% of the world's shorelines are subject to coastal erosion and sedimentation deficit

(Paskoff 1998; Miossec 2004). Moreover, sea level rise has been accelerating at a steady rate since the 1970s, reaching an average of 3.7 mm/year for the period 2006–2018 (IPCC 2022). On the other hand, anthropogenic pressure on coastal areas has increased significantly in recent years due to rampant urbanisation and high population concentration. According to Le Berre and Robert (2017), about 40% of the world's population lives within 100 km of the coast, and the population density of coastal cities is five times higher than the global average. These dynamics expose more people and property to coastal erosion.

Advances in geospatial technologies (GST) have enabled continuous and effective monitoring of shoreline changes. Numerous authors have used the photo-interpretation technique, in which the digital delineation of the shoreline is performed (Shoshany and Degani 1992; Thieler and Danforth 1994; Durand 1998; Juigner et al. 2012; Ford 2013; Kermani et al. 2016; Marzougui and Oueslati 2017; Paniagua-Aroyave et al. 2018; Bougherira et al. 2020). The operation is performed visually by the analyst to extract the shoreline. Space technologies such as LiDAR (Light Detection And Ranging), UAV photogrammetry, and very high-resolution satellite imagery are also used. These technological advances have facilitated shoreline monitoring and are characterised by increased accuracy, the ability to detect topographic variations, and seamless integration into geographic information systems (White and Wang 2003; Liu et al. 2007; Wang et al. 2023). However, the cost and limited accessibility of this technology, particularly for researchers in developing countries, pose significant challenges. In addition, the lack of historical data hinders the ability to detect long-term changes.

Remote sensing methods have been shown to be very effective in monitoring coastal dynamics at different spatiotemporal scales, as compared to field work (Pardo-Pascual et al. 2012). Landsat satellite imagery allows for regular and periodic monitoring of large land areas, providing a more comprehensive and continuous view of coastal zones (Boukhennaf and Mezouar 2023; Trinh et al. 2020). In fact, 40% of researchers have used Landsat satellite imagery to assess and quantify coastal evolution over the past 20 years (Apostolopoulos and Nikolakopoulos 2021). As a result, the combination of remote sensing and geographic information system (GIS) tools has been widely adopted by researchers for coastal monitoring (Ciritci and Türk 2019). The application of spectral

water indices, such as the Normalised Difference Water Index (NDWI) and the Modified Normalised Difference Water Index (MNDWI), is one of the most commonly used techniques that can effectively distinguish water-covered surfaces from land surfaces (Xu 2006). These indices, which are calculated from multispectral satellite imagery, facilitate the identification of shorelines (Ouma and Tateishi 2006; Pardo-Pascual et al. 2012; Trinh et al. 2020; Trinh et al. 2024). This technique ensures rapid and automated detection of coastal changes over large areas (Ciritci and Türk 2019; Alharbi et al. 2023; Boukhennaf and Mezouar 2023), contributing to continuous monitoring and proactive shoreline management (Bagheri et al. 2019; Awad and El-Sayed 2021; Fannassi et al. 2023; Kundu and Mandal 2024).

In Algeria, coastal erosion has received a particular attention in the National Climate Plan (Meer and Giz 2018) and in the National Strategy for Integrated Coastal Zone Management (Meer and CAR/PAP 2015), as it threatens coastal infrastructure and the environment. Many researchers have studied shoreline change using different methods and techniques. Most of them have used classical methods based on photo-interpretation of aerial photographs and/or satellite images (Ayadi et al. 2015; Bouhmadouche and Hemdane 2016; Kermani et al. 2016; Bougherira et al. 2020; Otmani et al. 2020; Kaddour et al. 2022). However, we found that optical remote sensing has been used very little (Boukhennaf and Mezouar 2023) and that previous studies have focused on small spatial scales of the Algerian shoreline. In contrast to the study by Rabehi et al. (2023), which used deep learning techniques to map sandy beaches along the Algerian shoreline, we highlight the lack of large-scale research, despite the availability of geospatial data from different sources covering the entire Algerian coastal zone.

In this study, we propose to fill this gap and attempt to understand the shoreline variations along the Algerian coast. This goal is achieved by using remote sensing and GIS techniques to extract the shoreline from Landsat satellite imagery using the Modified Normalised Difference Water Index (MNDWI) spectral matrix calculation method (Xu 2006). Then, we rely on a diachronic approach to monitor the Algerian shoreline changes using the Digital Shoreline Analysis System (DSAS) (Thieler et al. 2009), over the period 1986–2024 (38 years). In this context, shoreline monitoring is necessary to understand coastal change and to prevent and manage

the risks associated with coastal erosion (Clus-Auby 2003; Meeddm 2010; Al-Zubieri et al. 2020; Farhan and Lim 2013). At the land–sea boundary, the shoreline has been widely used by researchers as an indicator of coastal dynamics, namely coastal erosion and accretion processes, and for assessing coastal vulnerability (Nguyen et al. 2010; Kermani et al. 2016; Bougherira and Ghodbani 2019; Bamdadinejad et al. 2021).

Materials and methods

Study area

The Algerian coast is located in the south-western Mediterranean Sea and extends for ~1,622 km, crossing 14 wilayas (or departments) and 136 coastal municipalities (Meer and CAR/PAP 2015). It is subject to a Mediterranean climate with a strongly contrasting bioclimatic gradient. The west coast of Algeria, with an annual rainfall of ~300 mm and an average temperature of 18 °C, is part of the semi-arid bioclimatic zone. Contrary to the central and eastern coasts, where

rainfall varies from 600 to 1200 mm and average temperatures range from 18 to 20 °C, it oscillates between the sub-humid, humid and per-humid bioclimatic zones (Fig. 1).

The Algerian coast is characterised by a great diversity of geomorphological forms and sedimentological facies. From Marsat Ben M'Hidi in the west (on the Algerian–Moroccan border) to Cap Roux in the east (on the Algerian–Tunisian border), it is characterised by a succession of more or less open bays separated by more or less steep rocky coasts. There are cliffs of volcanic and metamorphic rocks, ~40 m high, in particular from Cap de Garde to Cap de Fer in Annaba, Cap Bougaroune in Skikda and Mont de Chenoua (Boutiba 2003). From Ghazaouat to Rechgoune (between Tlemcen and Ain Temouchent), from Cherrhell (Tipaza) to Tenes (Chlef) and from Tizirt (Tizi Ouzou) to Ziamia (Jijel) via Cap Carbon (Bejaia), there is also a series of cliffs carved out of Cretaceous limestone at different heights (Boutiba 2003).

Sandy coasts cover just over 65% of the Algerian shoreline (Rabehi et al. 2023), occupying the interior of bays and sheltering sandy beaches of varying widths. The latter, sometimes associated with coastal dunes,

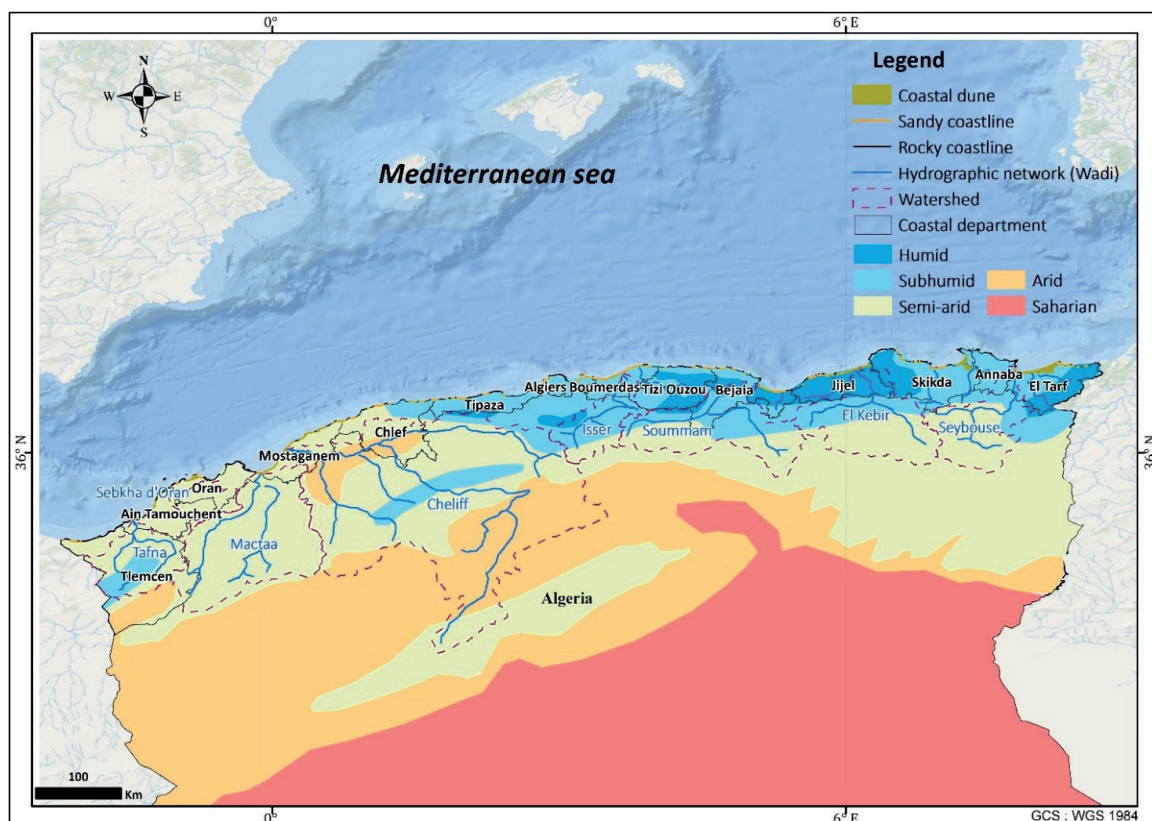


Fig. 1. Location of the study area, morphological, hydrographic and climatic context of the Algerian coast

develop downstream of the main exoreic watersheds where there is a significant source of sediment, such as the watersheds of Oued Chelif, Tafna, and Mactaa in the west, Oued Isser and Oued Soummam in the centre, and Oued El Kebir and Oued Sebous in the east (Bougherira 2021). In addition, coastal dunes sometimes persist downstream of small temporary rivers, dominated by large endorheic watersheds, which are less supplied with sediments of terrigenous origin, such as the coastal dune belts of Terga (Ain Temouchent) and Bousfer – Ain el Turck (Oran) on the west coast.

Methodology

In this research, we applied a diachronic approach based on the use of remote sensing and GIS techniques for the extraction and automated monitoring of shoreline changes at different spatiotemporal scales (Fig. 2).

Data collection

We used multispectral imagery from Landsat 5 TM (1986), Landsat 7 ETM+ (2000) and Landsat 8 OLI/

Table 1. Data used to monitor shoreline changes along the Algerian coast

Year	Sensor	Spectral Bands used (Spatial resolution in meter)	Number of images used
1986	Landsat 5 TM (Collection 2 Level 1)	6 optical bands (30 m)	13
2000	Landsat 7 ETM + (Collection 2 Level 1)	6 optical bands (30 m) 1 panchromatic band (15 m)	11
2014	Landsat 8 OLI/TIRS (Collection 2 Level 1)	8 optical bands (30 m) 1 panchromatic band (15 m)	10
2024	Landsat 8 OLI/TIRS (Collection 2 Level 1)	8 optical bands (30 m) 1 panchromatic band (15 m)	10

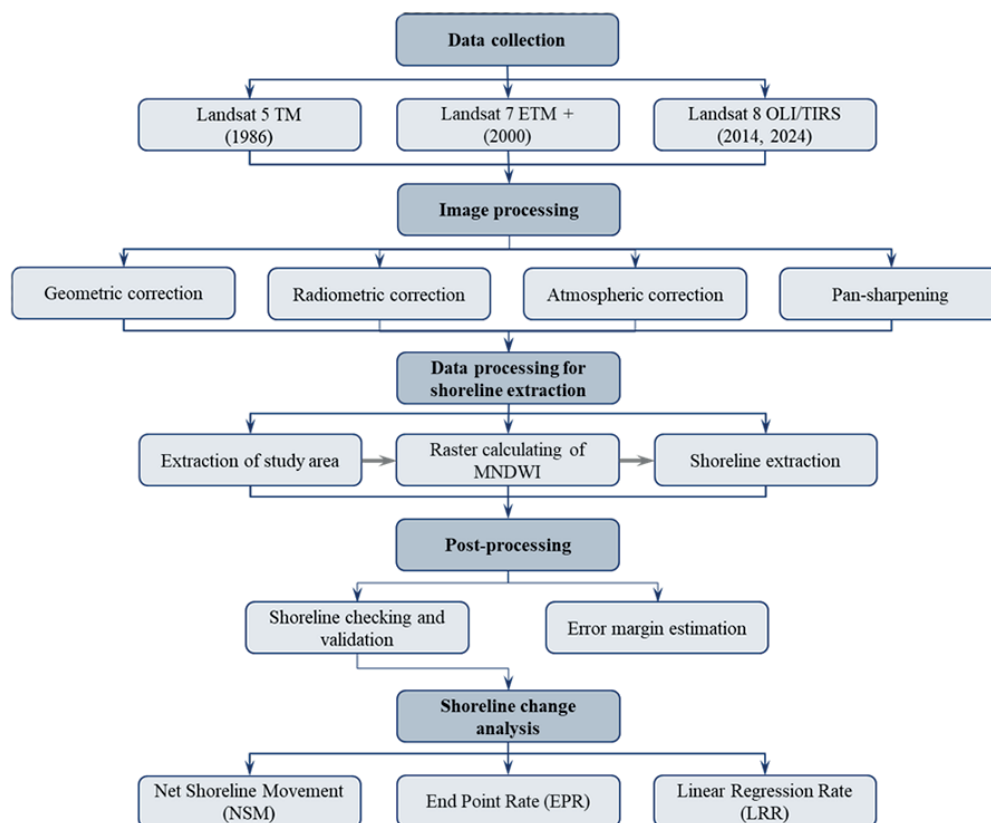


Fig. 2. Methodology flowchart for automated shoreline extraction and change analysis t

TIRS (2014, 2024), which are freely available on the United States Geological Survey website (USGS: <https://earthexplorer.usgs.gov/>). This collection of geospatial data, covering the period 1986–2024, makes it possible to analyse coastal changes over a 38-year period. The time intervals are more or less regular: 14 years for the periods 1986–2000 and 2000–14, and 10 years for the period 2014–2024 (Table 1).

When selecting the satellite images, we took into account the seasonality by downloading all the images during the summer period, between the months of June and August. We also selected images with low cloud cover (<10%). To cover the entire Algerian shoreline from east to west, 13 Landsat 5 TM (1986),

11 Landsat 7 ETM+ (2000) and 10 Landsat 8 OLI/TIRS (2014 and 2024) satellite images were required.

Image processing

In this phase, the satellite images were pre-processed, including atmospheric correction and spatial resolution enhancement (pan-sharpening) (Fig. 2), which was performed using QGIS Desktop 3.22 software. Atmospheric correction was performed using the Semi-Automatic Classification Plugin (SCP) tool, based on the DOS 1 (Dark Object Subtraction) model (Congedo 2021) to reduce the influence of

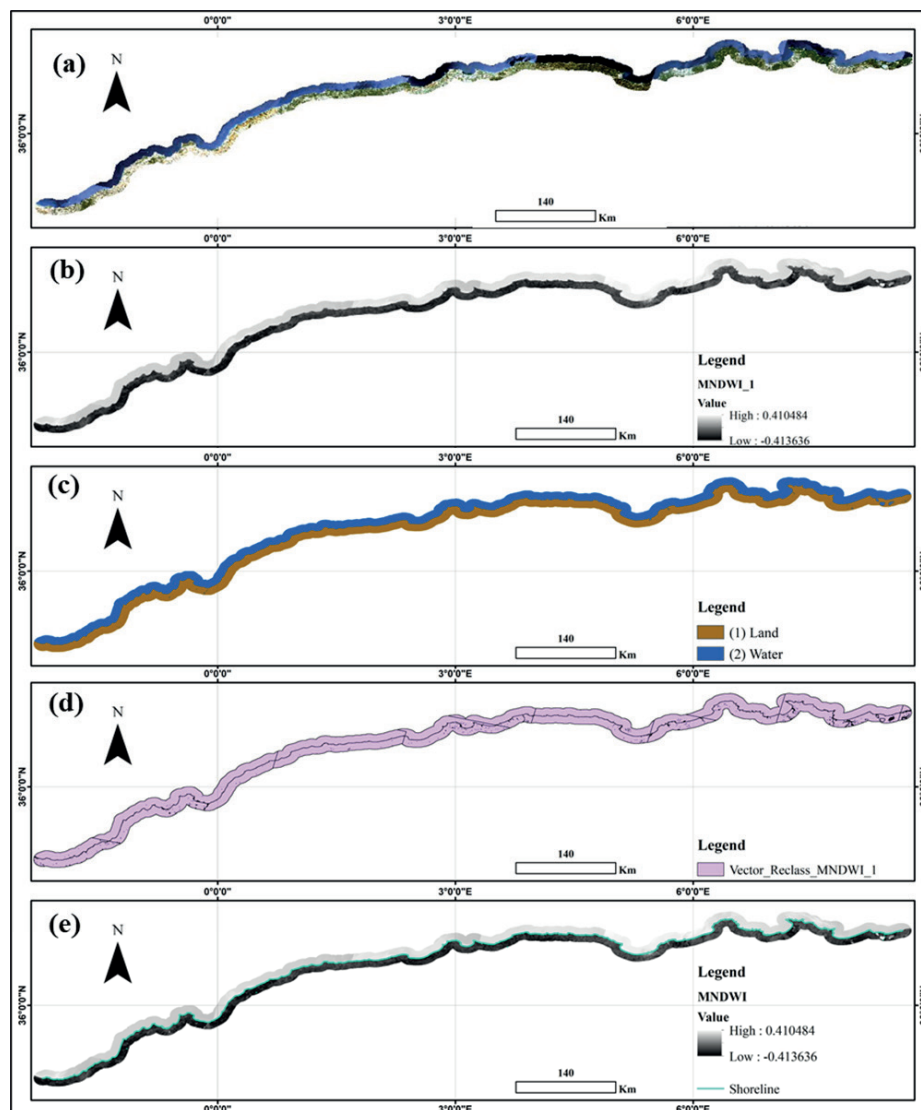


Fig. 3. Steps of shoreline extraction: (a) Study area extraction and band composition in real color, (b) MNDWI index calculation, (c) Raster reclassification, (d) Raster to polygon conversion, and (e) Shoreline extraction by converting polygon to line shapefile conversion

atmospheric particles on spectral bands and improve the sharpness of the satellite image. Likewise, pan-sharpening was applied to increase the spatial resolution of the 2000, 2014 and 2024 multispectral images. This involves combining the low-spatial-resolution spectral bands (30 m) with the high-resolution panchromatic band (15 m) using the Brovey algorithm (Du et al. 2007; Karathanassi et al. 2007). This combination produces images with better spatial resolution (15 m) while preserving spectral information. This pre-processing allows better extraction of the shoreline, making it easier to detect the land–sea boundary. Once these corrections had been applied to all the satellite images covering the study area, we proceeded to delineate the Algerian shoreline. A buffer of 10-km radius was used to isolate the study area (Fig. 3a). This step makes it possible to isolate only a part of the study area, to avoid processing excess data outside the coastal zone, and to optimise data storage and management.

Shoreline extraction

Once these corrections were applied, the images were ready for the next step of the analysis, which consisted of the shoreline extraction (Fig. 2). In fact, this step first required the raster calculation of the Modified Normalised Difference Water Index (MNDWI) spectral water index (Fig. 3b), which distinguishes water areas from land surfaces (Trinh et al. 2024; Xu 2006). The shoreline is then extracted by converting the raster results into vectors (SHP).

Calculation of the Modified Normalised Difference Water Index (MNDWI)

According to Xu (2006), the calculation of this MNDWI index is based on the use of the green and shortwave infrared 1 (SWIR 1) bands of the satellite image. The formula used is the following:

$$\text{MNDWI} = (\text{Green} - \text{SWIR 1}) / (\text{Green} + \text{SWIR 1}) \quad (1)$$

This formula applies a raster calculation to all pixels in the satellite image using QGIS software and the raster calculator tool. This allows us to generate a new MNDWI raster file for each part of the study area, up to the coverage of the entire Algerian shoreline (Fig. 3b). Positive values of this index indicate areas covered by water, while negative values represent land areas (Fig. 3c).

Extraction of the shoreline

After calculating the MNDWI, the second step is to extract the shoreline by converting the raster result into vector format. For this purpose, a thresholding operation was performed to clearly distinguish between water and land areas based on the MNDWI values. Pixels representing water areas were isolated, and the boundary between these pixels and land areas was interpreted as the shoreline (Fig. 3d). This was converted to a linear shapefile (SHP). This conversion allows for more efficient manipulation and visualisation of the shoreline (Fig. 3e). The SHP files extracted from all the satellite images are then used for monitoring and diachronic analysis of the shoreline.

To evaluate the accuracy of water object classification, the Kappa index and overall accuracy were used in the study. Table 2 presents the results of evaluating the accuracy of water object classification using the MNDWI index, as determined by the overall accuracy value and Kappa index.

The results show that classifying water objects using the MNDWI index has high accuracy. Compared to the other water indices (NDWI, ANDWI and AWEIsh), Trinh et al. (2024) confirm the superiority of the values obtained from the MNDWI.

Table 2. Accuracy of shoreline extraction using MNDWI

Satellite	Year	Accuracy (%)	Kappa (k)
Landsat 5 TM	1986	96	0.94
Landsat 7 ETM +	2000	96.2	0.945
Landsat 8 OLI	2014	96.6	0.95
Landsat 8 OLI/TIRS	2024	97.5	0.96

Post-processing

After the initial extraction of shorelines, a post-processing step is required to ensure the accuracy and validation of the results (Fig. 2). This step is carried out in two stages: verification and validation of the extracted shorelines, followed by evaluation of the associated error margins and uncertainties.

Verification and validation of the shoreline

As the first stage, the 1986 and 2000 shorelines were superimposed on the georeferenced topographic maps (1/50,000) of 1986 and the enhanced satellite images (pan-sharpening) of 2000, respectively. This stage allows us to visually check the superposition of the shorelines extracted from the satellite images and to correct any errors in order to validate them. Next, the shorelines extracted from the 2014 and 2024 images were exported in KML format and displayed in Google Earth Pro to compare their position with the high-resolution images. This protocol allows to visually verify the results and to correct and validate the position of the shorelines.

Estimation of error and uncertainty

The estimation of error and uncertainty is important in determining the accuracy of the results (Morton et al. 2004). In this context, we identified several sources of error, which were taken into account in the following formula to evaluate the total error margin (Et).

$$Et = \sqrt{Es^2 + Ep^2 + ERM_s^2 + Etd^2 + Esh^2} \quad (2)$$

where:

Es: Seasonal error, due to seasonal variations that can affect the position of the shoreline (extreme meteorological phenomena).

Ep: Pixel resolution error, related to the quality of the satellite data used, in particular the pixel size.

ERMs: Georeferencing errors, related to the image georeferencing process, which can lead to shifts in the position of the shoreline.

Etd: Tidal range error, related to tidal variations.

Esh: Shoreline extraction error, related to the accuracy of the algorithms and methods used to extract shorelines.

We also estimated the annualised error margin for the 38-year period according to the following formula (Kermani et al. 2016):

$$Ea(m/an) = \frac{\sqrt{Eti^2 + Et2^2 + Et3^2 + Et4^2}}{\text{Total Period (Years)}} \quad (3)$$

where:

Eti: Total error for year i.

Ea: Annualised total error.

The results of the error evaluation are summarised in Table 2. In fact, we estimate an average of error of 21.73 metres, as well as an annualised total error of 1.2 m/year relative to our assessment of the Algerian shoreline change.

Shoreline change analysis

In this study, the evolution of the Algerian shoreline was determined using the Digital Shoreline Analysis

Table 3. Estimation of the error

Year	1986	2000	2014	2024
Seasonal error (m)	0	0	0	0
Pixel error (m)	30	15 ^a	15 ^a	15 ^a
RMSE (m)	6.11	5.05	5.15	5.85
Tidal range error (m)	0.4	0.4	0.4	0.4
Extraction error (m)	15	7.5	7.5	7.5
Total shoreline position error (m)	34.10	17.52	17.55	17.77
Mean error (m)	21.73			
Period	1986-2000	2000-2014	2014-2024	1986-2024
Annualized error (m/yr)	2.74	1.77	1.78	1.20

(a) After pan-sharpening

System (DSAS) tool, an integrated extension of ArcGIS, over three time periods: 1986–2000, 2000–14, and 2014–2024. To do this, DSAS requires the creation of a database containing the different shorelines and a baseline drawn 300 m parallel to the oldest shoreline. We then create perpendicular transects 1500 m from the baseline and at 500 m intervals (Fig. 4). These transects are used to assess shoreline change by recording the position of the intersection between the transect and each shoreline.

The DSAS tool was used for its ability to automatically generate statistical parameters related to shoreline evolution, specifically Net Shoreline Movement (NSM), End Point Rate (EPR) and Linear Regression Rate (LRR). These allow us to observe and assess the nature of shoreline dynamics (Thieler et al. 2009), as follows:

- Net Shoreline Movement (NSM) measures the distance between two consecutive shoreline positions for each transect.
- End Point Rate (EPR) measures the rate of shoreline movement by dividing the distance between two consecutive positions by the number of years.

- Linear Regression Rate (LRR) provides a correlated estimate of shoreline change by fitting a linear regression to the data obtained for each period. The LRR takes into account all shoreline positions over time to better understand the trend in shoreline evolution over the long term.

Positive values of EPR, LRR, and NSM indicate seaward shoreline accretion, negative values indicate inland shoreline retreat, and zero values indicate stability. After determining the rates of shoreline change along the Algerian coast, we created seven

Table 4. Classification of shoreline change based on EPR and LRR (Natesan et al., 2015)

Shoreline change (m/yr)	Shoreline classification
≤ -2	Very High Erosion
$] -2 ; -1[$	High Erosion
$] -1 ; 0[$	Moderate Erosion
0	Stable
$] 0 ; 1[$	Moderate Accretion
$] 1 ; 2[$	High Accretion
≥ 2	Very High Accretion

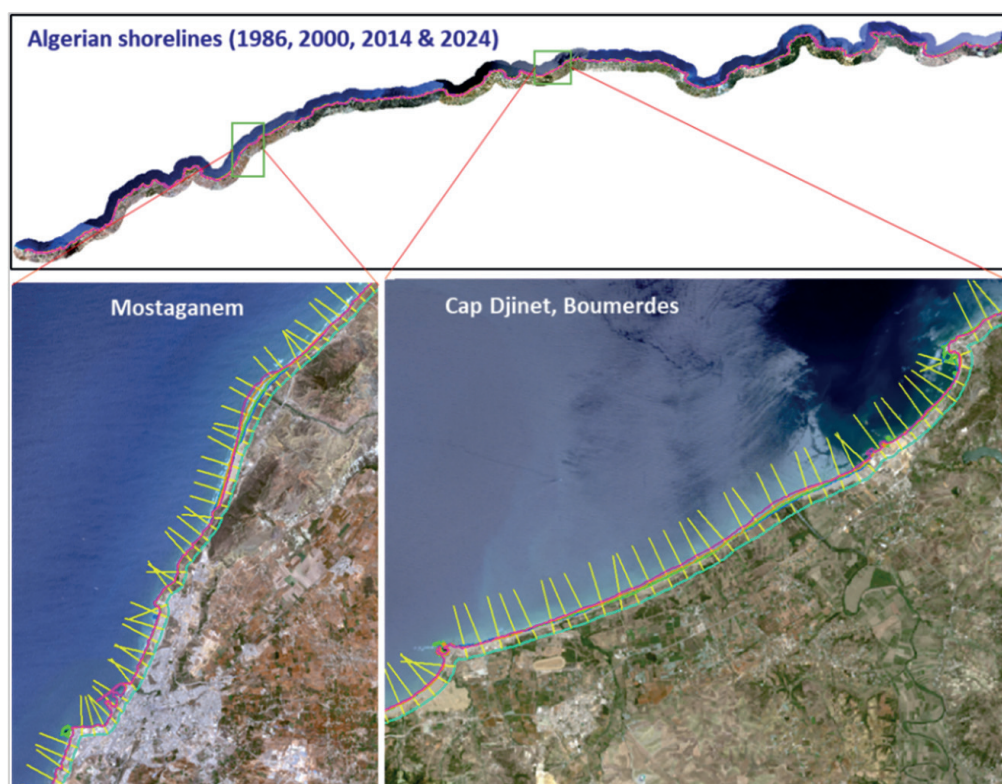


Fig. 4. Shorelines, baseline at 300 m back from the oldest shoreline and 1500 m transects at 500 m intervals, plotted for analysis of shoreline change.

classes encompassing erosion, stability and accretion (Table 4) following Natesan et al. (2015).

Results

The generated shorelines were integrated into a geographic information system using the WGS 1984 Universal Transverse Mercator (Zones 30, 31 and 32). The total length of the Algerian shoreline is 1683.88 km. This value is significantly higher than the 1622 km estimated as part of the national strategy for integrated coastal zone management (Meer and CAR/PAP 2015). According to Rabehi et al. (2023), the geometric length of the shoreline varies depending on the coordinate system used and, consequently, the impact of geodetic and ellipsoidal datums on the geometry of the shoreline needs to be assessed.

In this study, the analysis of the spatio-temporal variations of the Algerian shoreline was carried out on the basis of EPR, LRR and NSM statistics generated by the DSAS tool. The results show complex coastal dynamics, with marked regional disparities. They also show coastal dynamics favourable to erosion, with periodic variations fluctuating between periods of erosion and accretion (Table 5).

Short-term diachronic analysis of shoreline change

Shoreline change from 1986 to 2000

During the period 1986–2000 (14 years), the Algerian shoreline shows a predominantly erosive dynamic, with 75.40% of the shoreline in a state of erosion, 12.00% stable and 12.60% accumulating. Likewise, the average net retreat (NSM) is about –12.36 m for the whole shoreline, i.e. an average annual rate (EPR) of –0.88 m/year (Table 5), although the intensity and extent of this dynamic varies from one sector and/or department to another (Fig. 5).

In the western sector, the shoreline shows a less pronounced dynamic. The shoreline in the Department of Oran is relatively stable, with a slight advance of 0.511 m (NSM) and 0.037 m/year (EPR). By contrast, the shoreline at Mostaganem shows a significant retreat, with a NSM of about –8.92 m and an EPR of –0.64

m/year, reaching extreme values (NSM of –165 m) at the mouth of the Oued Cheliff. In addition, the Chlef Department records negative values for NSM (–14.9 m) and EPR (–1.064 m/year), indicating even more pronounced erosion.

Along the central coast of Algeria, significant variations in the position of the shoreline are also observed. The Department of Boumerdes recorded the most significant retreat, with extreme values exceeding

Table 5. Statistical results of the shoreline evolution by department, along the Algerian coast

Sector	Department	Length (Km)	1986-2000			2000-2014			2014-2024			1986-2024		
			NSM (m)	EPR (m/yr)	NSM (m)	EPR (m/yr)	NSM (m)	EPR (m/yr)	NSM (m)	EPR (m/yr)	NSM (m)	NSM (m)	EPR (m/yr)	NSM (m)
Western Sector	Tipaza	95.00	-0.256	-0.032	-3.589	-1.083	-15.168	0.667	6.672	-0.482	-13.582	-13.582	-0.357	-13.582
	Alger	108.01	-0.332	-0.037	-4.648	-0.918	-12.845	0.073	0.732	-0.524	-17.751	-17.751	-0.467	-17.751
	Boumerdes	182.45	0.037	0.037	0.511	-0.821	-11.490	0.135	1.347	-0.287	-8.124	-8.124	-0.214	-8.124
	Tizi Ouzou	124.00	-0.637	-0.637	-8.917	-1.176	-16.453	0.713	7.127	-0.606	-18.388	-18.388	-0.484	-18.388
	Chlef	119.39	-1.064	-1.064	-14.898	0.099	1.393	0.601	6.015	-0.097	-6.754	-6.754	-0.178	-6.754
Central Sector	Tipaza	137.87	-0.612	-0.294	-8.576	-0.562	-7.861	0.428	4.281	-0.325	-10.184	-10.184	-0.268	-10.184
	Alger	102.41	-0.294	-1.755	-4.126	-0.766	-10.719	2.014	20.147	-0.042	0.091	3.459	0.091	3.459
	Boumerdes	78.74	-1.755	-0.678	-24.575	-0.660	-9.241	0.730	7.300	-0.669	-25.005	-25.005	-0.658	-25.005
	Tizi Ouzou	62.72	-0.678	-0.678	-9.494	0.786	11.004	0.223	2.228	0.108	0.014	0.541	0.014	0.541
Eastern Sector	Bejaia	115.02	-1.498	-1.159	-20.981	0.376	5.269	0.988	9.885	-0.103	-1.216	-1.216	-0.032	-1.216
	Jijel	129.12	-1.159	-1.221	-16.221	0.432	6.044	0.044	0.446	-0.322	-16.808	-16.808	-0.442	-16.808
	Skikda	215.42	-1.221	-1.962	-17.089	0.116	1.626	0.315	3.157	-0.238	-11.857	-11.857	-0.312	-11.857
	Annaba	110.97	-1.962	-0.716	-27.462	1.181	16.526	0.388	3.877	-0.033	-6.440	-6.440	-0.169	-6.440
	El Tarf	102.76	-0.716	-0.883	-10.031	-0.143	-2.005	1.778	17.782	0.063	0.129	4.891	0.129	4.891
Total		1683.88	-0.883	-0.883	-12.359	-0.222	-3.113	0.602	6.019	-0.218	-7.637	-7.637	-0.201	-7.637

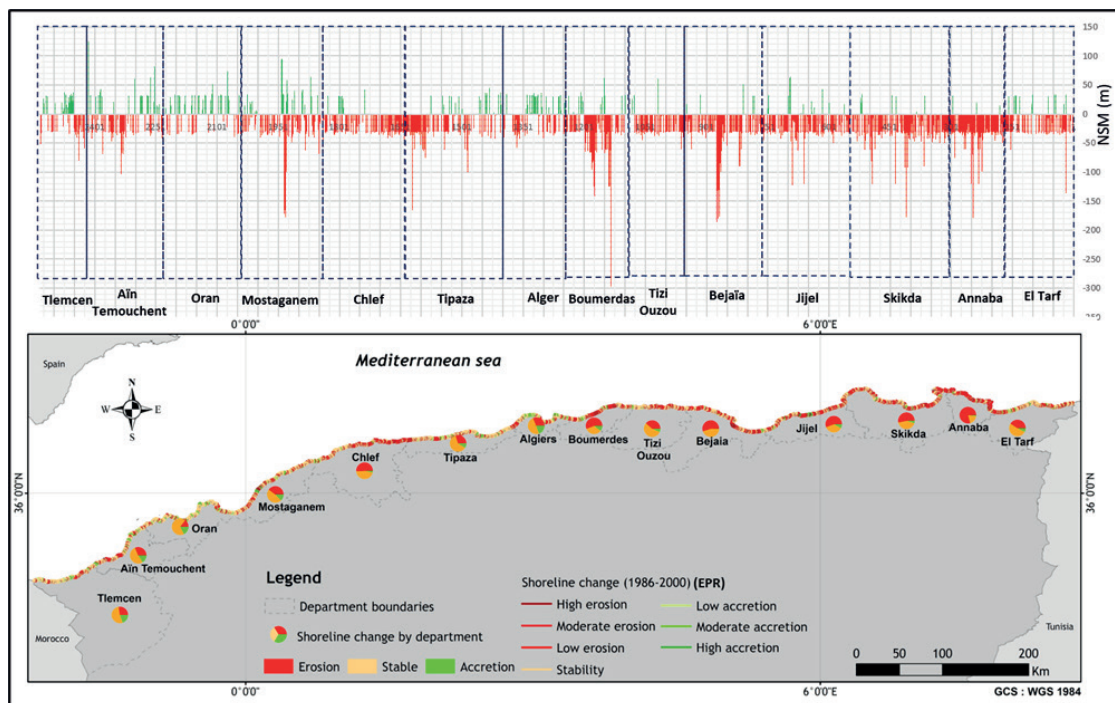


Fig. 5. Evolution of the Algerian shoreline from 1986 to 2000

–150 m NSM, recorded along the beaches located between the mouth of the Oued Isser and Cap de Djinet. The average retreat values for Boumerdes are around –1.755 m/year (EPR) and –24.575 m (NSM), much higher than the values recorded in Tipaza and Tizi Ouzou, which show a less erosive dynamic. The Algiers shoreline, on the other hand, shows a relatively stable and lower rate of retreat, estimated at –0.294 m/year.

In eastern Algeria, the Departments of Bejaia, Jijel, Skikda and Annaba recorded significant values of shoreline retreat. These departments are among the most vulnerable to coastal erosion, with average values of shoreline change ranging from –1.16 m/year and –1.22 m/year (EPR) in Jijel and Skikda, respectively, to –1.96 m/year (EPR) in Annaba. However, the most significant shoreline retreat in eastern Algeria reached extreme values of more than –160 m (NSM), especially in Bejaia. In El Tarf, erosion is present but less pronounced than in the rest of the eastern departments, indicating local variability in coastal dynamics.

Shoreline change from 2000 to 2014

For the period 2000–2014, the results show contrasting shoreline dynamics from one coastal sector to another, ranging from accretion to more moderate

erosion than in the previous period (see Table 5). In fact, 31.27% of the Algerian shoreline is eroding, 46.35% is stable and 22.38% is accumulating (Fig. 6).

In the western sector, the departments most affected by coastal erosion are Mostaganem and Tlemcen, with average shoreline changes of –16.453 m and –15.168 m (NSM) and –1.176 m/year and –1.083 m/year (EPR), respectively. Extreme values of shoreline retreat have also been recorded, particularly in Mostaganem, at around –150 m (NSM), especially in the most dynamic coastal zones, such as the mouth of the Oued Cheliff in Mostaganem. This coastal dynamic is associated with a proliferation of hydraulic dams upstream of the Oued Cheliff, which deprive the downstream beaches of large amounts of terrigenous sediment. The shoreline of Oran suffered a significant retreat, with an NSM of –11.490 m and an EPR of –0.821 m/year, while the shoreline at Chlef became relatively stable, with a slight accretion estimated at 1.393 m (EPR of 0.099 m/year), in contrast to the previous period. Significant erosion particularly affected the sandy beaches of Bousfer, ranging from –30 to –50 m, indicating values comparable to those highlighted by Bougherira et al. (2020).

Significant changes were observed along the central coast of Algeria. At Algiers, the shoreline continues to retreat, with an NSM of –10.719 m and an EPR of –0.766 m/year. However, the shoreline of the

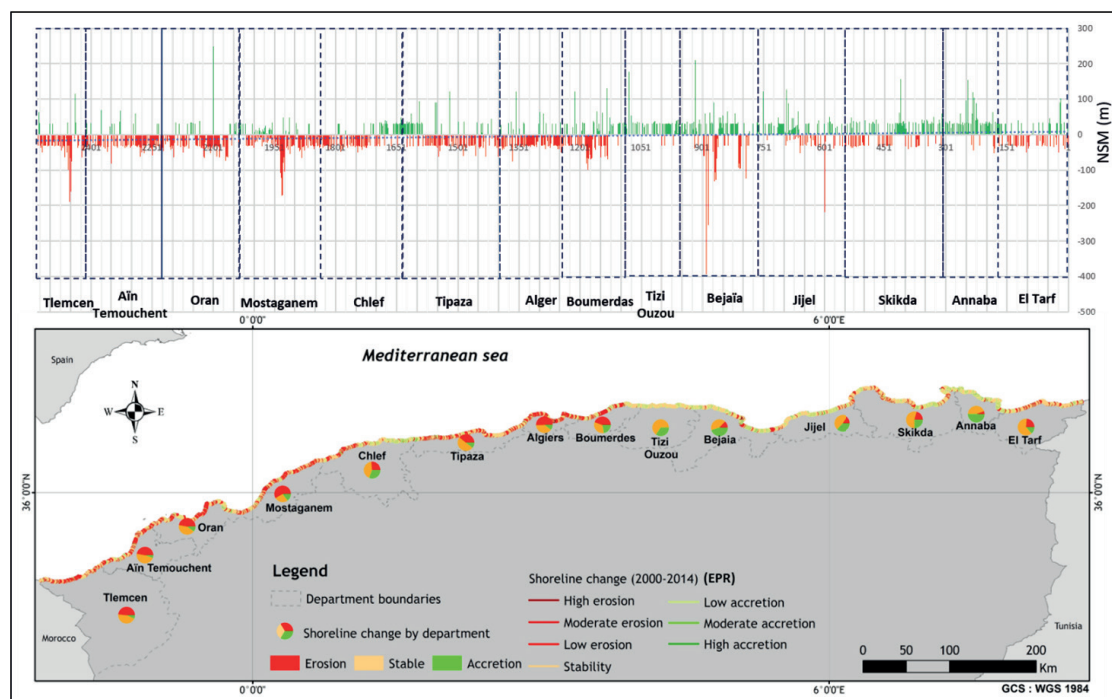


Fig. 6. Evolution of the Algerian shoreline from 2000 to 2014

department of Boumerdes shows a significant slow-down of the retreat compared to the previous period, with an NSM of -9.241 m (EPR of -0.660 m/year). These results are comparable to those obtained by Boukhennaf and Mezouar (2023) and Otmani et al. (2020) for the coast of Algiers. On the other hand, the shoreline of the department of Tizi Ouzou shows favourable accretion dynamics, with an NSM of 11.004 m and an EPR of 0.786 m/year.

Similarly, the Departments of the eastern sector showed an overall favourable accretion dynamic. During this period, the shoreline of Annaba shifted from generalised coastal erosion to a coastal dynamic favourable to accretion (NSM: 16.526 m; EPR: 1.181 m/year), thus representing the coastal zone with the highest accretion in Algeria. The coastal areas between Bejaia, Jijel and Skikda also showed a positive trend of shoreline change, with NSM values of 5.269 m, 6.044 m and 1.626 m, respectively. Finally, the El Tarf region showed a significant decrease in shoreline retreat, with an NSM of -2 m and an EPR of -0.143 m/year.

Shoreline change from 2014 to 2024

During the period 2014–2024, we observed a remarkable change in the global trend of shoreline evolution, in favour of accretion and stabilisation. In fact,

29.48% of the Algerian shoreline is characterised by erosion, 17.43% by stabilisation, and 53.17% by accretion (Fig. 7). As a result, we recorded an average net accretion of 6.019 m (NSM), i.e. an average accretion rate (EPR) of 0.602 m/year (see Table 5), indicating an overall trend of moderate accretion in the sense of Natesan et al. (2015).

Along the western coast of Algeria, the Mostaganem shoreline shows a clear transition towards accretion dynamics, with an NSM of 7.127 m and an EPR of 0.713 m/year. The Oran and Tlemcen coasts also show positive accretion trends, although local areas of erosion remain. On the other hand, the Ain Temouchent shoreline shows a very low accretion rate, with an NSM of 0.732 m and an EPR of 0.073 m/year, reflecting a stabilisation of the shoreline position.

In the central coast of Algeria, the Algiers shoreline recorded a very high accretion rate, with an NSM of 20.147 m and an EPR of 2.014 m/year, probably related to successful coastal management projects (Otmani et al. 2020; Boukhennaf and Mezouar 2023). On the other hand, the Boumerdes and Tizi Ouzou coasts show moderate accretion, with NSM of 7.300 m and 2.228 m and EPR of 0.730 m/year and 0.223 m/year, respectively.

On the eastern coast of Algeria, a significant advance in the position of the shoreline was observed. For example, the shoreline at El Tarf shows a strong

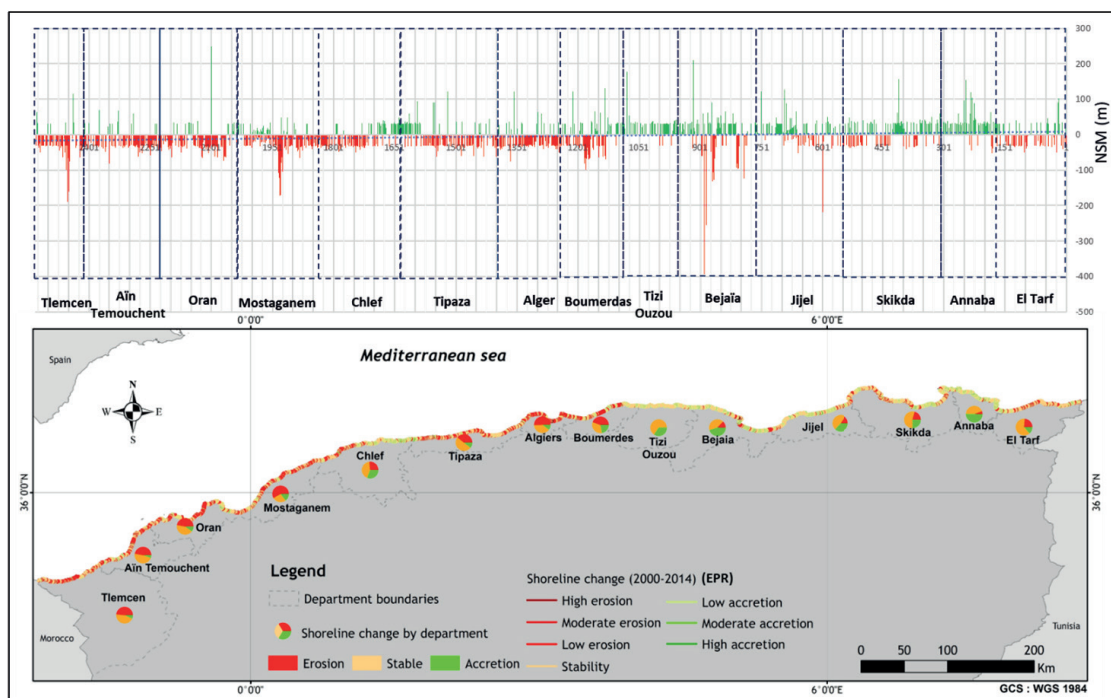


Fig. 7. Evolution of the Algerian shoreline from 2014 to 2024

accretion, with an NSM of 17.782 m and an EPR of 1.778 m/year. On the other hand, the shorelines of Annaba and Jijel showed a decrease in the rate of accretion compared with the previous period 2000–14, reaching NSMs of 12.649 m and 5.598 m, respectively. However, the Bejaia and Skikda shorelines continues to accrete, with NSMs of 9.885 m and 3.157 m, respectively.

Long-term Sshoreline change from 1986 to 2024

The shoreline evolution results obtained using the EPR and LRR parameters for the period 1986–2024 show a strong correlation between these two statistical parameters, with R^2 equal to 0.89 (Fig. 8), whose comparison confirms the consistency between the two parameters. However, the LRR is more suitable for a reliable assessment of coastal change in the long term, since it considers all shoreline positions in the long term, unlike the EPR, which calculates the rate of change between two successive positions.

Analysis of the short-term results highlights a significant transition in the evolution of the Algerian shoreline, ranging from accelerated erosion between

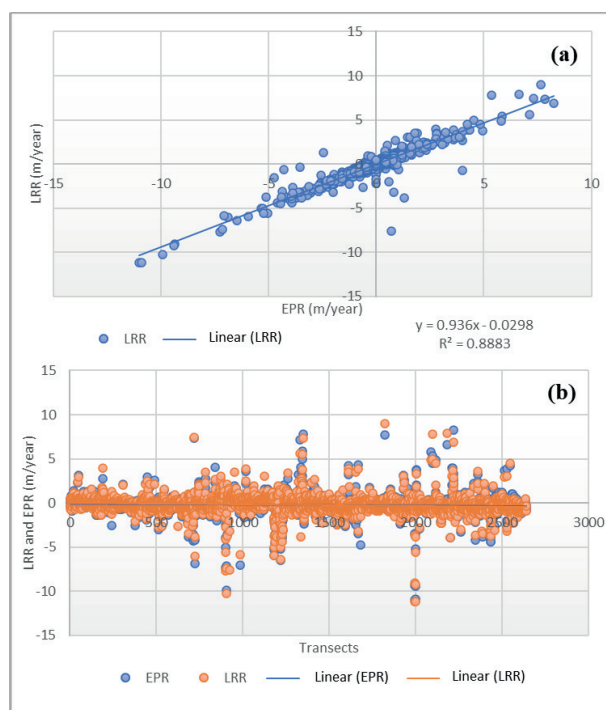


Fig. 8. (a) Correlation of shoreline change rates obtained by EPR and LRR statistics (m/yr); (b) Comparison of EPR and LRR values (m/yr) calculated along all transects (2642) in the study area over the period (1986-2024)

1986 and 2000, a stabilising trend between 2000 and 2014, and dominant accretion during the period 2014–24 (see Table 5). However, the spatial analysis of the results over the long-term period (1986–2024) reveals a strong heterogeneity of coastal dynamics along the Algerian shoreline, with a significant tendency towards shoreline retreat (Fig. 9). In fact, 55.4% of the shoreline is eroding, 16.64% is stable, while 27.96% is accreting. Moreover, the average NSM is estimated at -7.637 m, indicating moderate erosion, and the EPR and LRR values, respectively -0.201 m/year and -0.218 m/year, respectively, confirming a global trend of coastal erosion (see Table 5).

On the west coast of Algeria, the results show a general trend of erosion, with NSM values of up to -18.388 m and rates of change of -0.606 m/year in the Mostaganem department. The coasts of Tlemcen and Ain Temouchent also record significant retreats of -13.582 m and -17.751 m, respectively, in terms of NSM, and LRRs of -0.482 m/year and -0.524 m/year. The shoreline of Oran underwent moderate erosion with a NSM of -8.124 m and an LRR of -0.287 m/year.

Along the central coast of Algeria, the department of Boumerdes is the most affected, with an NSM of about -25 m and an LRR of about -0.67 m/year, highlighting high erosion. On the other hand, the coast of Algiers shows a slight accretion, with low positive

values for NSM (3.459 m) and LRR (0.042 m/year), probably linked to coastal management projects and marine erosion defence engineering. The coast of Tizi Ouzou department is relatively stable, with an LRR of 0.108 m/year.

On the east coast, the Jijel and Skikda shorelines show significant retreat, with NSMs of about -16.8 m and -11.9 m, respectively, and LRRs of -0.322 m/year and -0.238 m/year. The El Tarf coast, on the other hand, shows a slight accretion, with NSM of 4.891 m and LRR of 0.063 m/year.

Discussion

The analysis of the variations of the Algerian shoreline during the period 1986 to 2024 (38 years) reveals a general trend of coastal erosion, the intensity of which corresponds to periodic fluctuations involving erosion, accretion and stabilisation. Moreover, Algeria's sandy coasts, which occupy more than 65% of the shoreline (Rabehi et al. 2023), have been significantly affected by coastal erosion, although they are naturally favourable to accretion. This observation is consistent with the idea of a sediment deficit (Paskoff 1998) and a reversal of the global trend in

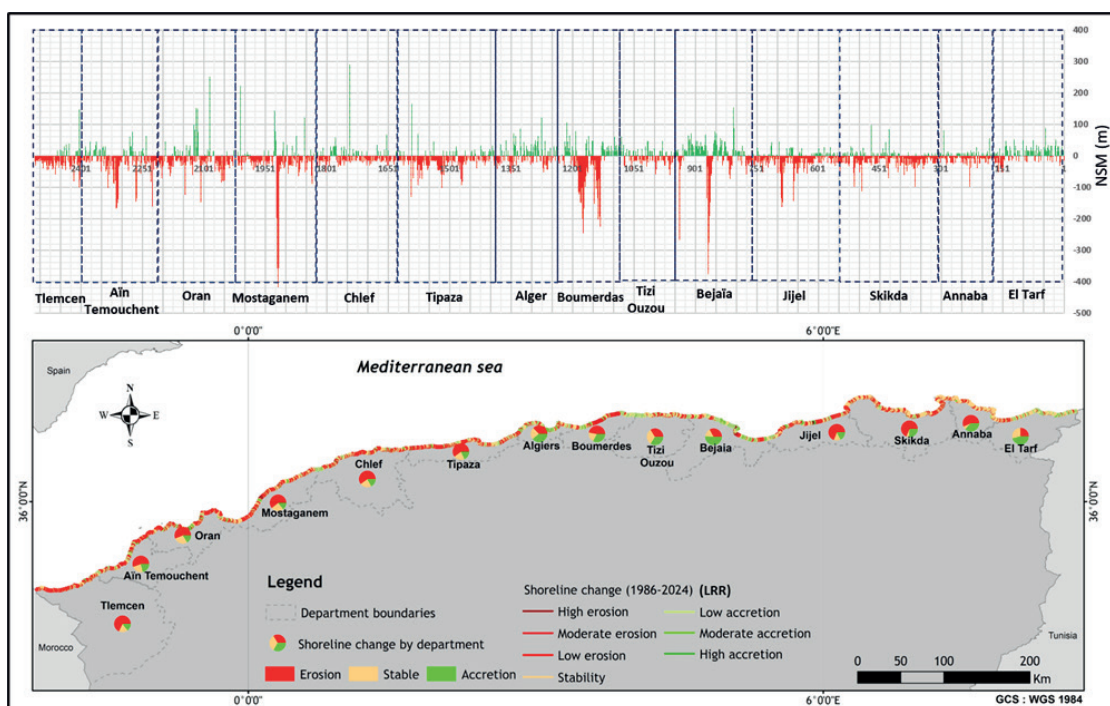


Fig. 9. Evolution of the Algerian shoreline from 1986 to 2024

the evolution of the Mediterranean and world coasts, likely driven by sea level rise due to climate change (IPCC 2022). These coastal dynamics are influenced by a number of natural and anthropogenic factors, the consequences of which vary from region to region.

Along the west coast, the highest rates of shoreline retreat are recorded in Mostaganem (about -0.6 m/year: LRR). According to Sallaye et al. (2025), shoreline retreat in Mostaganem would be the consequence of the contemporary sea level rise and longitudinal sediment transport, generated by waves and currents from the north-north-east sector, while also identifying the anthropogenic consequences, linked to unplanned urbanisation and socio-economic development, on shoreline retreat. Indeed, during the 2000s, numerous construction, seaside tourism and industrial projects were implemented to the detriment of coastal dunes, despite the Coastal Law No. 02-02, which protects them (Ghodbani et al. 2016; Taibi 2016; Senouci and Taibi 2019; Senouci et al. 2021). Coastal dunes play an important role in the nourishment and sediment budget of sandy beaches. The degradation of coastal dune systems generally results in a sediment deficit on the associated beaches, increasing their vulnerability to coastal erosion (Bougherira et al. 2020). In addition, the presence of dams on the Cheliff and Kramis wadis (rivers) results in sediment trapping and thus a significant reduction in sediment supply. These terrigenous sediment inputs are necessary for beach nourishment and coastal sediment balance.

The shoreline of the departments of Ain Temouchenet and Tlemcen has retreated by an estimated -17.75 m and -13.58 m, respectively, mainly due to the development of coastal built-up areas, illegal sand mining (Ghodbani et al. 2015; Yahia Meddah et al. 2023) and strong hydrodynamics (Amarouche and Akpinar 2021; Amarouche et al. 2022). The study conducted by Boukhennaf and Mezouar (2023) shows that the Algiers coast underwent accretion during the period 1984–2021, mainly due to the importance of solid inputs from the Oued El-Harrach and coastal protection works. The submarine morphology plays a crucial role in the morpho-sedimentary equilibrium of beaches, which can be manifested by the attenuation or amplification of wave energy. According to Kaddour et al. (2022), Bou-Ismaïl Bay has a bathymetry that favours the dissipation of wave energy and, consequently, has an erosion-reducing effect. Boukhennaf and Mezouar (2023) explain this as the result of the combined effect of hydrodynamic factors

and excessive sand removal from the beaches and dunes. In addition, this retreat of the shoreline is also due to the reduction of sediment supply to the beaches of Boumerdes following the construction of the Beni Amrane and Kadara dams. According to LARID (2002), the construction of dams upstream of exoreic watersheds in Algeria has led to a 75% reduction in the sediment discharged by wadis.

The shorelines of Jijel and Skikda have experienced significant erosion rates, estimated at about 16.8 m and 11.8 m, respectively. According to several authors, illegal sand extraction from dunes and land artificialisation in Jijel have exacerbated coastal erosion by preventing sediment supply to the beaches (Boutiba 2006; Kermani et al. 2016; Bougherira and Ghodbani 2019). The shoreline retreat in Annaba and Bejaia is estimated at average values ranging from -6.44 to -1.21 m, respectively. According to Ayadi et al. (2015), the acceleration of coastal erosion in Bejaia is attributable to coastal artificialisation, protection structures, coastal dune degradation and beach sand extraction. In fact, as Ayadi et al. (2025) demonstrated, there is significant multidecadal variability in the shoreline along the western coast of the Bay of Bejaia, confirming the coexistence of erosion and accretion processes depending on local geomorphological and hydrodynamic conditions. In addition, the unfavourable hydrodynamic conditions due to the exposure of the shoreline to winter waves from the northern and north-western sectors accentuate coastal erosion (Amarouche et al. 2022). Similarly, Belhout et al. (2025) demonstrated the significant role of extreme wave dynamics and storm propagation in the formation of coastal hazards along the central Algerian coast, which could partly explain the spatial variability observed in shoreline changes in our results.

In Annaba, shoreline retreat is mainly due to “littoralisation” and expansion of industrial areas, which interfere with the natural dynamics of the shoreline. The most noticeable impact is undoubtedly the extraction of sand from the beaches, despite the fact that this practice is formally prohibited by law (*Loi du Littoral* 02-002). In fact, sand extraction accelerates the erosion of beaches and affects their sedimentary balance; in the long term, the affected beaches suffer a significant loss of surface area and become more vulnerable to marine erosion, which also leads to socio-economic losses (Taibi 2014). Furthermore, Zerrouki et al. (2025) provided concrete evidence of the impact of upstream dam construction on sediment transport and coastal retreat, particularly at river

mouths. This finding is consistent with the significant erosion observed in our study near major river mouths, such as those of the Cheliff and Soummam rivers, where sediment trapping likely contributes to a coastal sediment deficit.

Conclusion

In our research, we analysed the changes in the Algerian shoreline for the period 1986–2024, i.e. 38 years. Multispectral images from Landsat satellite imagery were used, combining remote sensing and GIS techniques. First, the shorelines of 1986, 2000, 2014 and 2024 were extracted, after preprocessing, using the MNDWI water spectral index. Subsequently, we were able to track shoreline changes using the Digital Shoreline Analysis System (DSAS) tool, generating statistical data such as End Point Rate (EPR) and Net Shoreline Movement (NSM). These data have allowed us to determine the erosion phenomenon on a national scale. However, it is important to mention certain methodological limitations, namely the margin of error, mainly due to the spatial resolution of the satellite images and the extraction of the shoreline. This can affect the accuracy of the results, although this margin of error is acceptable for studies carried out on a large spatial scale. The analysis of the results obtained shows a general trend of coastal erosion, with 55.4% of the shoreline subject to coastal erosion. Nevertheless, we were able to identify fluctuations in the trend of coastal change in Algeria, as well as some very pronounced regional disparities. Between 1986 and 2000, there was a strong erosion trend, with 75% of the shoreline affected by retreat. Coastal erosion then began to decrease between 2000 and 2014, when 31.27% of the Algerian shoreline was affected, while 46.35% was stable and 22.38% was accumulating. On the other hand, during the period 2014–24, a shoreline accumulation rate of 53.17% was observed. The results obtained in this article are not intended to replace local studies, which are potentially more accurate and intended for operational use, but to provide additional information on a broader scale. As a follow-up to this scientific work, our research perspectives are oriented towards a multi-criterion assessment of coastal vulnerability at the national scale, integrating a series of climatic, hydrodynamic, geomorphologic and socio-economic parameters.

Disclosure statement

No potential conflict of interest was reported by the authors

Author contributions

Study design: AB, TG; data collection: AB, RS; statistical analysis: AB, RS, N-ET, TG, VA-B; interpretation of results: AB, RS, N-ET, TG, VA-B; preparation of manuscript: AB; literature review: AB, RS.

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