



# Assessment of shoreline dynamics on the Eastern Coast of Algiers (Algeria): a spatiotemporal analysis using in situ measurements and geospatial tools

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## Abstract

The eastern coast of the Algiers, which stretches over 15 km, is currently experiencing very intense socioeconomic and urban development that is causing severe disturbances to the coastal environment. The main issue of this study concerns itself with understanding the evolutionary trends of this system and assessing its state of vulnerability towards erosion phenomena. This work focuses on the historical study of the variation in the shoreline position by combining photogrammetry data and in situ DGPS measurements (Differential Global Positioning System). Data treatment was carried out using a geographic information system (GIS) and the Digital Shoreline Analysis System (DSAS) geostatistical computing tool. These techniques have enabled identification of the erosion/accretion rates and description of the evolutionary trends over a period of 58 years by calculating the net rates of coastline changes over three time periods (1959–1980, 1980–2003 and 2003–2017). The results show that the net rate fluctuates between sites, with an overall tendency towards erosion (49% of the coastline), associated with a significant variation in the average annual rates. The computed statistics show that the study area was in a state of accretion between 1959 and 1980, with an average end point rate (EPR) equal to 0.72 m/year. This net rate of change turned negative and became alarming during the period between 1980 and 2017 when the EPR decreased to  $-0.54$  m/year. These trends are due to a combination of the cumulative effects of storms and anthropogenic actions. Hence, sustainable management policies must be developed rapidly by coastal managers to rehabilitate the area.

**Keywords** Erosion · Shoreline · Coastal vulnerability · DGPS · DSAS · Eastern Algiers · GIS · Geomorphology

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## Introduction

Coasts are the centres of numerous natural processes that give them significant mobility (Aedla et al. 2015), sometimes accentuated by anthropogenic actions (Hellequin et al. 2013). Coastal erosion, whether natural or anthropogenic, causes ecological damage, economic loss and consequent social problems (Rigoni 2003; Colas 2007). In the mid-1980s, an international investigation showed that, overall, coasts worldwide receded along 70% to 80% of their length during the twentieth century (Pilkey and Hume 2001); this trend is found on most urbanized coasts worldwide (Meur-Ferec and Morel 2004). According to Alquini et al. (2016), erosion processes are far from slowing down, and beach erosion is a worldwide issue that causes significant losses, such as economic setbacks, environmental damage and social problems. The situation has become very alarming on several Mediterranean coasts, where the erosion rate is unprecedented (Rigoni 2003).

On a smaller scale, the eastern coast of Algiers constitutes a system vulnerable to erosion and marine submersion. This coastal zone, threatened by many natural (storms) and anthropogenic factors (plunder of the sand on the beach) (Bouhamadouche 1993), is currently experiencing very intense socio-economic and urban development (EgisEau/Iau-Idf/Brgm 2013), which threatens erosion and a modification of the coastal environment. For that purpose, understanding shoreline recession trends is needed.

Sustainable development of coastal zones and effective management of erosion risk are based on the monitoring of coastal evolution at different time scales (MEEDDM 2010; Rasuly et al. 2010). The mapping of this coastal risk could be useful for the implementation of strategies at various levels of government.

This work is part of a research project oriented towards the prediction of the vulnerability of the Algiers coastal system for risk management purposes. This article aims to present a diagnosis of the risk of erosion threatening the coastal system through mapping erosion that affects the study area.

A series of repeated observations over a long period as well as a rigorous comparative measurement of the coastline position will allow for a real erosion diagnosis (Paskoff and Clus-Auby 2007; DGPR 2014). This work consists of monitoring the coastline mobility over a period of 58 years using a Geographic Information Systems (GIS), which allows the integration of multi-data sources (e.g. aerial photographs, satellite imagery and DGPS surveys), which can provide information on erosion/accretion trends that are analysed and mapped (Moore 2000; Morton et al. 2005; Hapke and Reid 2007). This process should help highlight coastal variations by associated software, such as DSAS.

## Study region

The area of interest is the eastern coast of Algiers, located on the western boundary of Zemmouri Bay and situated between  $36^{\circ}46'96''$  and  $36^{\circ}48'54''$ N and lies between the longitudes of  $3^{\circ}14'10''$  and  $3^{\circ}20'45''$ E. Stretching from the Cape of El Marsa in the West to Reghaia in the East, the 15 km coastline is characterized by the presence of several morphological systems (Fig. 1).

This area is part of the large Mitidja basin, where two sub-watersheds can be found: the sub-basins of the El Hamiz River and the Reghaia River (Fig. 1). The latter, with a length of approximately 17.13 km, is the most important stream (CAR/ASP-PNUE/PAM 2015). The study area has a Mediterranean climate characterized by 8 months of mild and humid cooler periods and 4 months of dry and warm summer conditions. An analysis of the average monthly temperatures recorded by the National Office of Meteorology (ONM) between 2004 and 2016 shows that the summer season, from May to October, is characterized by relatively mild temperatures with averages ranging from 19.31 to 26.40 °C. During the winter season, the coldest month is February, with an average temperature of 10.83 °C. The rainiest period extends from September to May with a maximum average rainfall of 116 mm in December, whereas the summer period is practically dry.

The statistical analysis of the Medatlas dataset (1999–2004) indicates two types of wind. During summer, the prevailing winds come from the East to the North-East sector with an incidence frequency of 61.6%, while in winter, the winds are from the West to the South-West with a frequency of 48%.

Analysis of the annual and seasonal occurrence frequencies of swells by direction, presented by the statistical series of the same Medatlas cruise, showed that the dominant swells originate from the West (27% of the time) annually, with a higher occurrence of frequency of 34% in winter, and from the North-East sector 43%, with a higher occurrence frequency of 66% during summer.

For significant wave heights, the West and North-East are the sectors where the agitations seem to be the most frequent. According to Benghoufa et al. (2016), the dominant swells at this level are characterized by significant heights, generally oscillating between 0.25 and 2.5 m.

The Mediterranean coast has a low-tidal range (not significant), and the microtidal range does not allow tidal currents that are able to influence sedimentary distribution. The dominant swells create a western drift current, which seems to be a significant factor in sedimentary transport.

The attractive nature of the eastern side of Algiers makes it an excellent tourist spot and a place of interest that records the highest rates of attendance in the city of Algiers (EgisEau/Iau-Idf/Brgm 2013). Nevertheless, the zone is characterized by very important littoralization and anarchic urbanization. Concrete walls and rock-filled dykes were built at the cliffs of Kaf El Arar to protect the various endangered dwellings. Two

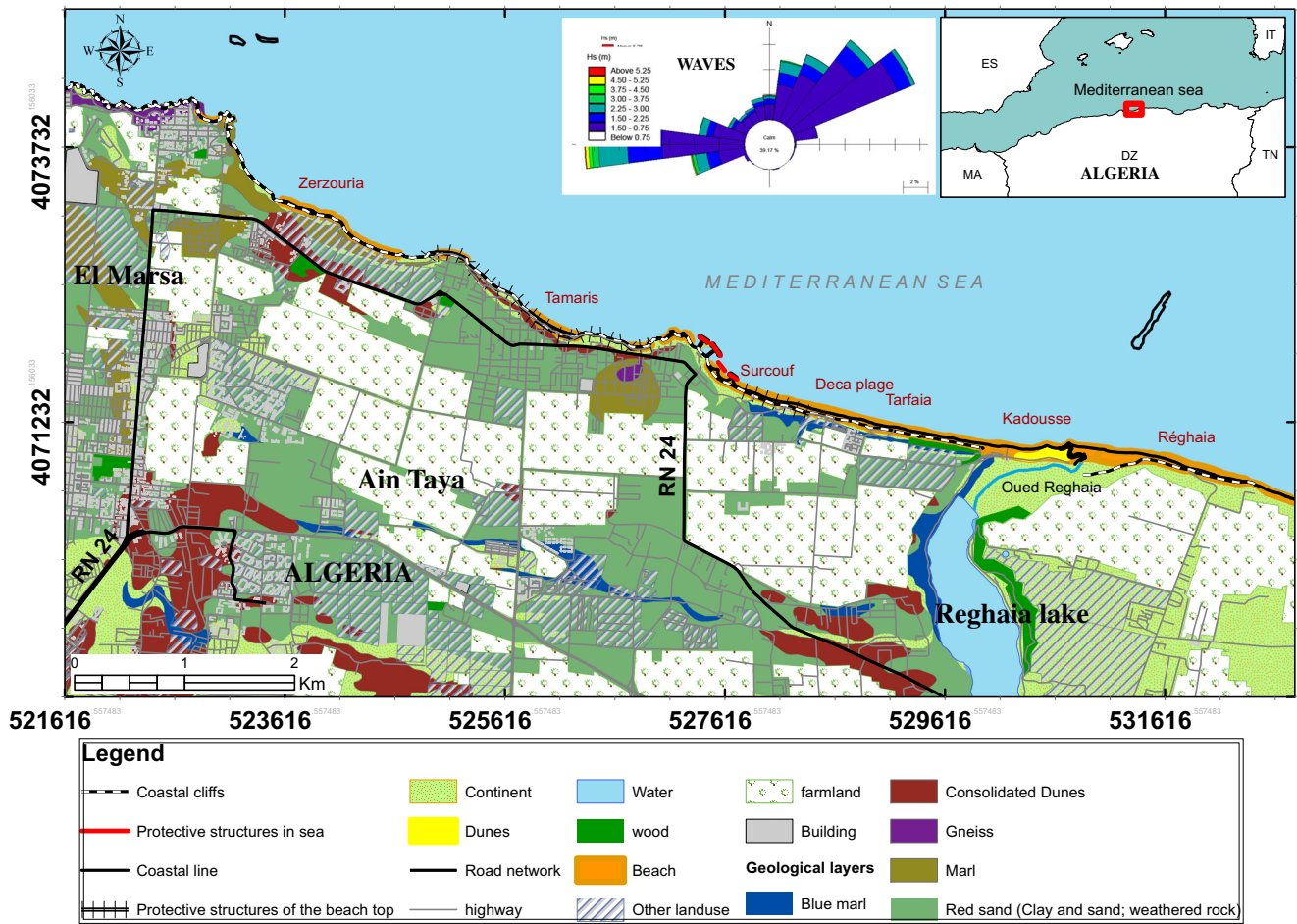


Fig. 1 Geographical location of the study area

breakwaters, which permit the regeneration of the beach by forming a tombolo in front of the west breakwater, were set up at Surcouf beach in the western region of the study area (Fig. 1).

### Methods

To work over a much longer period of time as much as possible, it is necessary to make a spatio-temporal study of the coastal evolution by comparing the shorelines extracted by both modern and classical techniques. The aim of this work is to establish a monitoring of coastline kinematics by conducting in situ surveys during the study period using a direct technique that provides high-resolution results (DGPS surveys). The DGPS surveys are then combined with the coastlines extracted from iconographic supports (aerial photos) to make a diagnosis of the evolution over a time period of 58 years.

The adopted methodology was proposed by the French Geological and Mining Research Office (BRGM). The choice of a coastline monitoring technique must be part of a logical progression of steps (Bulteau et al. 2011), according to the

available data and the indicator of the coastline (Boake and Turner 2005).

The analysis of the type of coastal environment (backshore to shoreface) is necessary to characterize the geographical and geomorphological context of the area, hence, to acquire a global knowledge of the studied sector (Bulteau et al. 2011; MEEDDM 2010). The studied coast includes a varied geomorphology marked by the presence of both natural and artificial coastal forms. Through field observation and satellite imagery, the presence of wide beaches, sand dunes and cliffs of considerable heights has been observed, as well as artificialized coastal areas by the implementation of protective structures (i.e., groynes and breakwaters) and buildings at the water’s edge.

Therefore, to address these issues, reference to the most appropriate coastline indicators (dune borders and the limits of vegetation and berms) is needed (Boake and Turner 2005); it is also important to take into consideration the coastal types in the study area and the available data sources (Dolan et al. 1980; Robin and Levoy 2007; Faye 2010; MEEDDM 2010).

Several DGPS surveys were carried out in the study area, and the most recent survey (2017) was selected to establish an

up-to-date diagnosis of the dynamics and to merge the current survey with those of older coastlines for the evaluation of the coastline kinematics on a larger scale. The most commonly applied technique to detect visible reference lines is visual interpretation performed either directly by in situ measurements or indirectly on an iconographic document (aerial photographs, images or maps) (Boake and Turner 2005).

The extraction of the shoreline from the aerial photos has some geometric limits. The use of DGPS data considerably reduces the cumulative error (centimetric precision); however, such data types were not available in Algeria before 2008. The possibility of comparing this type of data allows for the establishment of a more accurate diagnosis.

Aerial photos are most commonly used for coastline mapping (Moore 2000). Their diachronic analyses are well adapted to determine the shoreline changes (Suanez and Simon 1997; Durant 1998; Aernouts and Héquette 2006). Shorelines are identified by grey scale tonal variations. Offering the possibility of comparing results with multi-source historical data (Elabdellaoui and Ozer 2007), aerial photographs help to achieve better management of these fragile environments (Durant 1998). Nevertheless, they have several geometric distortions (Thieler and Danforth 1994), which may introduce some risks associated with errors (Aernouts and Héquette 2006).

Aerial photos (Table 1) from 1959, 1980 and 2003 were processed by using computer-assisted photo interpretation, and shorelines were extracted after georeferencing and orthorectification of the aerial photographs in the WGS 84 system.

DGPS surveys are a direct approach based on periodic topographic measurements using a Differential Global Positioning System (DGPS) (Faye 2010). The survey principle consists of using two receivers, one mobile (rover) and one fixed (base), that serves as a reference (Kara 2009; Bulteau et al. 2011). The mobile GPS is positioned in real time by receiving the corrections emitted by the base station. This is deployed in a specific and temporary way, installed above a marker or geodetic point of known coordinates. The network of these geodetic points is maintained by the Algerian Littoral Promotion and Protection Agency (APPL-Algeria) to obtain a centimetre accuracy of x, y and z coordinates; this method does not require any special post-processing before exporting to a GIS (POC 2000). As part of the study, the DGPS helped to

conduct coastline surveys in all types of accessible environments. In a microtidal range context, such as the Mediterranean coast, the recommended coastline indicator is the instantaneous wet/dry limit, according to the fact that aerial photographs are taken during a calm period. This choice is also based on the type of available historical data.

The survey was carried out under very calm sea conditions and conducted throughout the entire area without interruption to exclude any eventual changes. The land side of the protective structures has been considered as the shoreline to fill gaps.

The surveys were carried out in RTK mode (real-time kinematic) using two acquisition methods: auto-topo and point topo:

- Continuous topo (auto-topo) is used to acquire continuous points for the coastline survey, using a regular acquisition as a function of time (for a walk, one point taken every 2 s for our surveys).
- Point topo is used when acquiring landmark points (rivers).

After acquiring the aerial photos and preparing the DGPS surveys, the treatment was based essentially on the use of GIS software. This permits detailed maps showing the variations in the coastline between 1959 and 2017, and graphs that display the evolution of the coastline over the same period through the Digital Shoreline Analysis System (DSAS), which also allows the calculation of the evolution rates of the coastlines by several statistical methods (Thieler et al. 2005). The first step consists of extracting data recorded and stored in the internal memory of the computer associated with the DGPS, then processing the data using GIS software, digitizing the measured points to assemble all the shorelines. This step is performed after each DGPS survey. The extraction and processing of the coastline from aerial photographs were performed using ArcGIS software 10.3 and the DSAS extension. For this study, the aerial photos were processed during the AMISmap III project (AMIS 2008).

The DSAS permitted transects of 300 m in length to be traced with a fixed equidistance of 20 m. The transects were manually adjusted in some areas where the coastline is highly deformed (Fig. 2). The shoreline variation calculations were performed along the 423 transects across seven beaches in the studied zone, with the exception of an inaccessible sector of Ain El Beida area (municipality of Ain Taya), which is an artificial rocky coast (seawalls) (Figs. 1 and 9e).

Five main statistical parameters, namely, the net shoreline movement (NSM), the shoreline change envelope (SCE), the end point rate (EPR), the linear regression rate (LRR) and the weighted linear regression rate (WLR), were calculated by the DSAS. These parameters are used to establish a diagnosis of the coastline evolution. In this study, the EPR and the NSM were retained.

**Table 1** Years and scales of aerial photos (AMIS 2008)

Year of the coastline	Acquisition method
1959	Aerial photography at 1/25,000
1980	Aerial photography at 1/10,000
2003	Aerial photography at 1/10,000
2017	DGPS



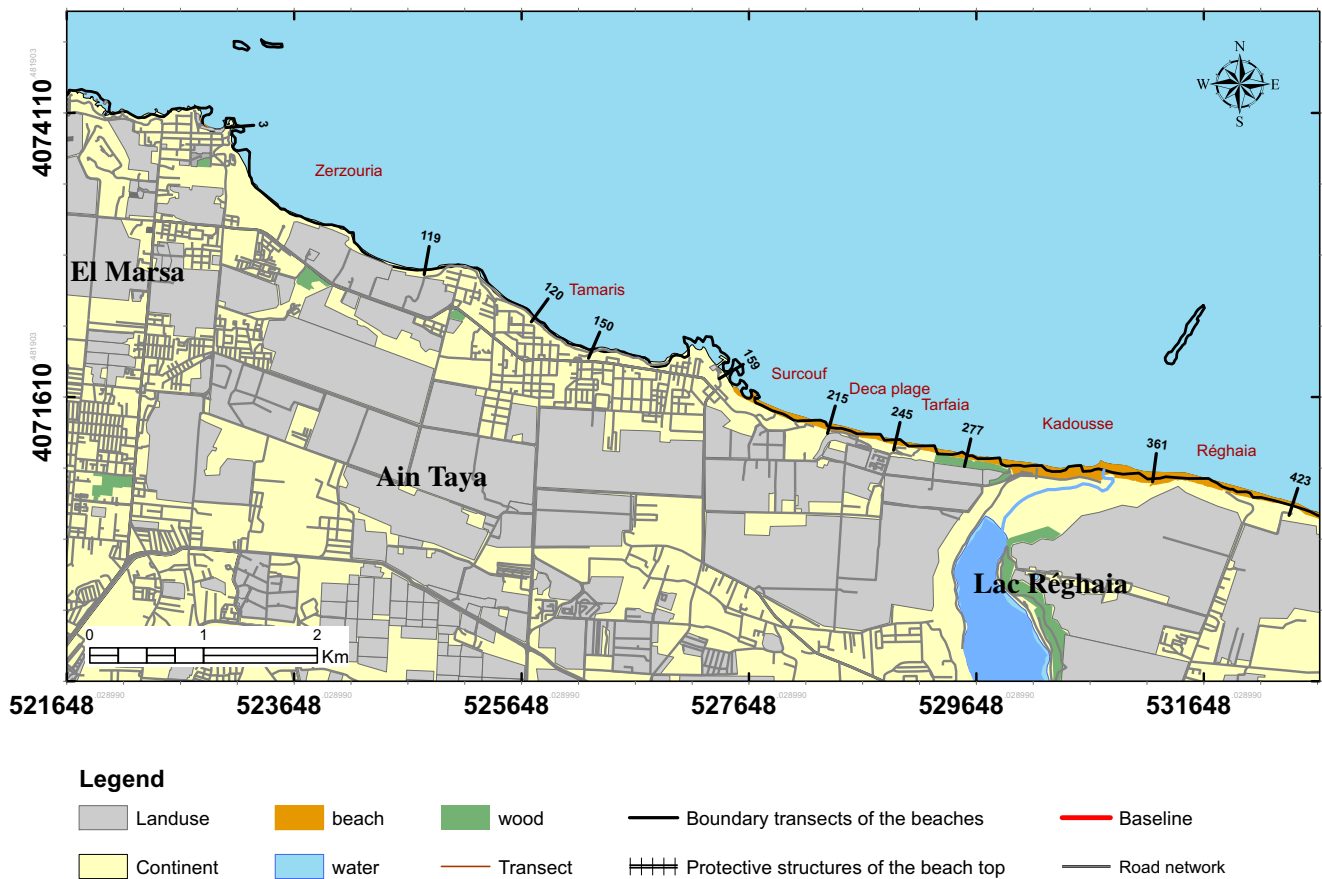


Fig. 2 Distribution of transects along the western shore of the studied zone

The EPR is a statistical parameter that describes the course and distances travelled by coastline variations (Himmelstoss 2009). It is a rate calculated by dividing the distance between the position of the initial shoreline (1959) and the most recent year (2017) by the elapsed time (58 years). The main advantage of the EPR is its ease of calculation and the minimum requirements for input data (two coastlines) (Van-To and Thao 2008).

According to several authors (Crowell et al. 1991; Romine et al. 2009; Virdis et al. 2012; Kermani et al. 2016), different sources of errors related to the position of the coastline are possible. To estimate the total uncertainty, these sources of error must be taken into account. Each aerial photo has the following errors: (1) a digitization error is considered to be 0.2 mm, so considering a generic scale of  $\frac{1}{N}$ , the deviation from the actual ground position is  $0.2 * N$  mm. (2) The root mean square error (RMS) defines the difference (distance) between the ground control point (GCP), which is the reference point on the satellite image (QuickBird), and the GPC on the aerial photo during the georeferencing process. (3) An additional error may be introduced by the resolution of the rasters; it can be estimated at approximately half a pixel. In other words, the error relative to the resolution of the image is more or less  $\frac{1}{2}$  of the dimension of the pixel. In addition, the coastline is affected by the tide. (4) For most old photos, tide data are not

available, not forgetting that the distance travelled by the wave on the beach also depends on the slope of the beach.

The total uncertainty relative to the position of the coastlines extracted from the aerial photos was estimated to be  $\pm 3$  m (AMIS 2008).

The uncertainty entailed by the DGPS is mainly due to the inclination of the mobile station during the development of the surveys by the operator and the precision of the line of the coastline. Table 2 summarizes the estimated values for these errors:

In fact, the uncertainty is calculated automatically with the DSAS application. The ECI is the margin of error related to the EPR calculations, and it can be calculated over small periods of time or over the entire period of study (Kermani et al. 2016) by the following equation:

$$ECI = \frac{\sqrt{(Et A)^2 + (Et B)^2}}{\text{date (A)} - \text{date (B)}}$$

where

- (Et A) is the uncertainty of the position of shoreline A
- (Et B) is the uncertainty of the position of shoreline B
- date (A) is the date of the shoreline A survey
- date (B) is the date of the shoreline B survey

**Table 2** Estimated errors of a DGPS survey

Error source	Estimated error
GPS System	± 3 cm
Inclination of the mobile station	± 2 cm
Digitization of the coastline	± 25 cm
Total error	± 30 cm

To illustrate the diachronic change in the shoreline position, maps have been produced, and a diachronic order of evolution between a recent and an old coastline is represented by a colour code. This code is established according to a norm of a standard shade, starting by the warmest colour, which represents the most recent year, to the coldest colour (Faye 2010).

## Results

Beaches are a naturally dynamic environment, even on seasonal timescales. The progress of the shoreline, presented by the NSM, shows a maximum of accretion at the Reghaia and El Kadouss beaches with net advancement rates of approximately 64 m and 61 m, respectively. This is mainly due to the supply of sediment carried by the Reghaia River, as well as the presence of the dune ridge, which provides an equilibrium to the sedimentary dynamics. However, a maximum recession of 51 m is recorded at Surcouf Beach and, more precisely, in the zone between transects 210 and 215. Indeed, since 2014, the area of Surcouf has been administratively subdivided into the following two parts:

- Les Flots Bleus, where the installation of the defence structures allowed local protection; however, the sedimentary transport of this cell ended up in a disturbance state.
- Hay El Chouhada, where the installation of the structures at the adjacent beach had a strong direct impact on the sediment supply. The maximum recession was recorded after the storm of March 12, 2015. Since then, riprap protection has been established at this part of Surcouf beach (Fig. 8a–d).

### Analysis of the coastline evolution between 1959 and 2017

The results are displayed in the EPR (m/year) and NSM (m), representing the minimums, maximums and averages of shoreline changes. The positive and negative values of the EPR allow calculation of the percentages of coastline in erosion and accretion. These percentages are displayed in Table 3.

A diachronic analysis of the coastline was carried out over three different periods: 1959–1980, 1980–2003 and 2003–2017. Additionally, to scan the whole area of study, the analysis during the last period was divided into two sectors:

- Sector 1: The western side, including the portion extending from the western extremity of the area to Ain El Baydha, between transects 1 and 150.
- Sector 2: The eastern side, situated between transects 151 and 423

Table 3 shows that before 1980, 69% of the coastline was experiencing accretion, and 31% was being eroded. From 1980 to 2003, a change in trend was noticed. The erosion rate doubled to 62%, while the accretion rate decreased to 38%. In the third period (1959–2017), a further increase in erosion (69% of the coastline) was observed. These findings led us to extend the study towards a periodic evolution based on the EPR/NSM statistics, so as to identify the causes and understand their impacts on the coastal dynamic.

### Period from 1959 to 2017

For this period, the global EPR is +0.07 m/year; this value shows that the zone presents a slight accretion (Fig. 3). However, the temporal analysis indicates very important erosion that occurs throughout the zone. Field observations show that the geomorphology of sector 1 is characterized by lively marine cliffs (Fig. 8f), whose orientation is very favourable to hydrodynamic attacks; in particular, storms swell from the West, North-West and North sectors, for which cliff heights generally reach between 3.5 and 5.5 m (Benghoufa et al. 2016).

Globally, over the total period of the study, this sector shows significant erosion that evolves with time and space. A retreat of 42 m was noticed at the Zerkouria cliffs with an average EPR of  $-0.17$  m/year. This caused a loss of 1.81 ha of the total beach area (Table 4). Tamaris Beach also experienced strong erosion with an EPR of approximately  $-0.27$  m/year. Marine attacks (Fig. 8c) and the removal of sediment towards the offshore (Fig. 8b) are the main factors governing this erosion; this is probably due to the hydrodynamic activities, waves and currents that can be accentuated due to the reflective nature of these beaches. The same observations are noticed in sector 2, which is experiencing a double evolution characterized by significant erosion in the Surcouf zone (EPR =  $-0.58$  m/year, loss of 3.48 ha) and Decaplage (EPR =  $-0.27$  m/year, loss of 1.04 ha). These values are directly related to the length of the beaches. The reflection process can be observed on all types of coasts with frontal waves (beaches, protective structures and cliffs). For reflective beaches, the process of erosion is induced by both the wave obliquity and the slope. The multiple factors and the complexity of the process in the marine environment make the erosion

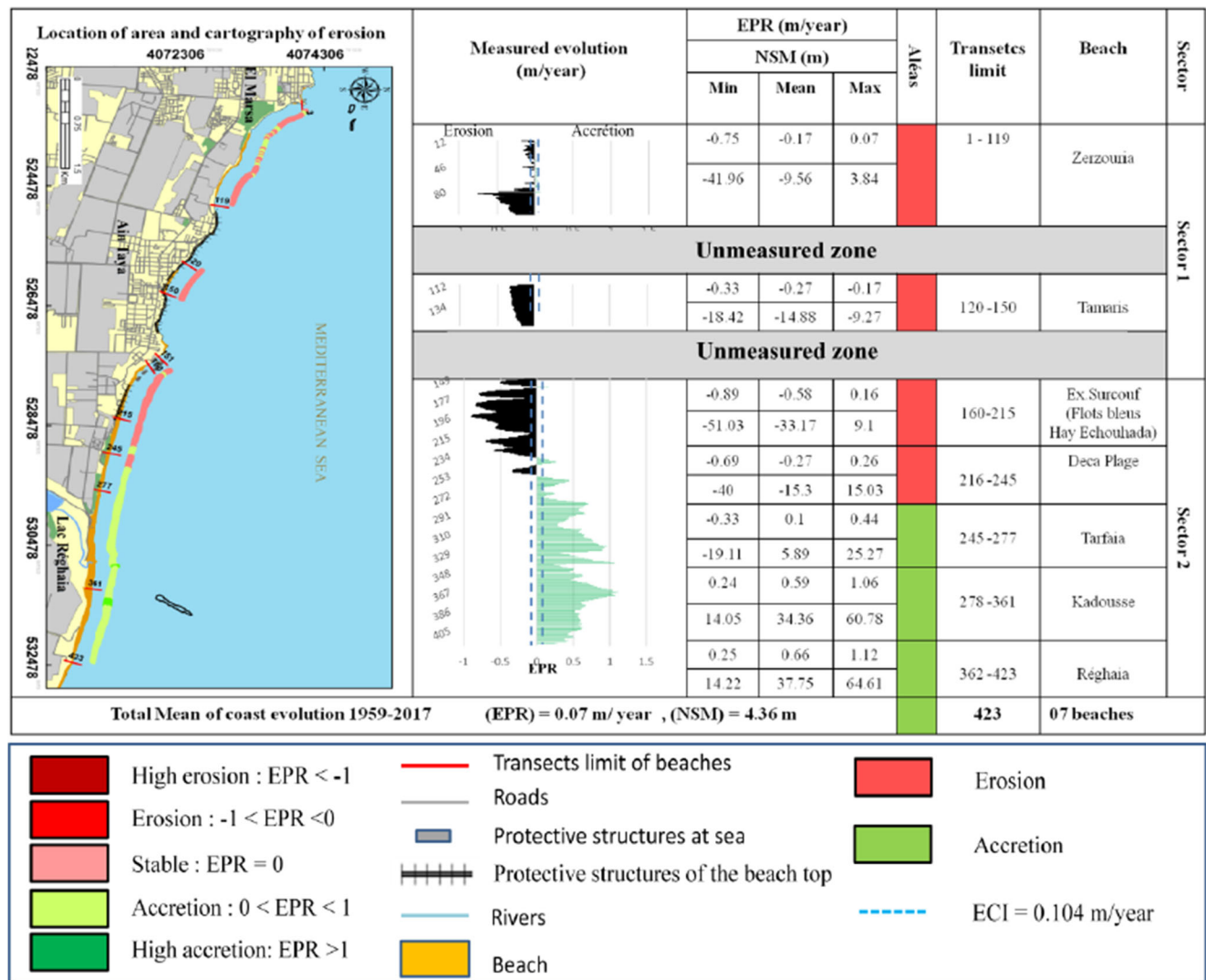
**Table 3** Percentage of the coastal linear evolution state along the east of Algiers

	1959–1980		1980–2003		2003–2017		1959–2017	
	Erosion	Accretion	Erosion	Accretion	Erosion	Accretion	Erosion	Accretion
Coastal linear (km)	4.65	10.35	9.3	5.7	10.35	4.65	7.35	7.65
Total evolution state (%)	31	69	62	38	69	31	49	51

phenomenon difficult to predict. The anthropogenic action and the defence infrastructures (Fig. 8d) can also cause a disturbance of the sediment transport. Currents seem like the transport factor of the sediment, leaving only some parts sheltered at Surcouf to form tombolos or other forms of accumulation.

In contrast, in the same period, the maximum values of the EPR and NSM are observed in the sandy beaches of Tarfaia, El Kadouss and Reghaia. For the last 58 years, the EPR has been on the order of 0.50 for these beaches.

evolution of the area, El Kadouss beach presents a maximum gain of 5.77 ha during this period. Reghaia River (Fig. 8e) and the dune of El Kadouss (Fig. 8g) represent the main sources of the sedimentary flow and provide a compensatory contribution to the losses, especially during periods of storms. Likewise, the study by Bouakline (2009) has shown that these beaches are dissipative and therefore can be favourable to accumulation. Unlike the area of Ain Taya, the backshore area in this sector is uninhabited, which reduces anthropogenic action, although it remains omnipresent. The



**Fig. 3** Statistical synthesis of coastline kinematics and coastal erosion mapping in the period 1959–2017 on the eastern coast of Algiers

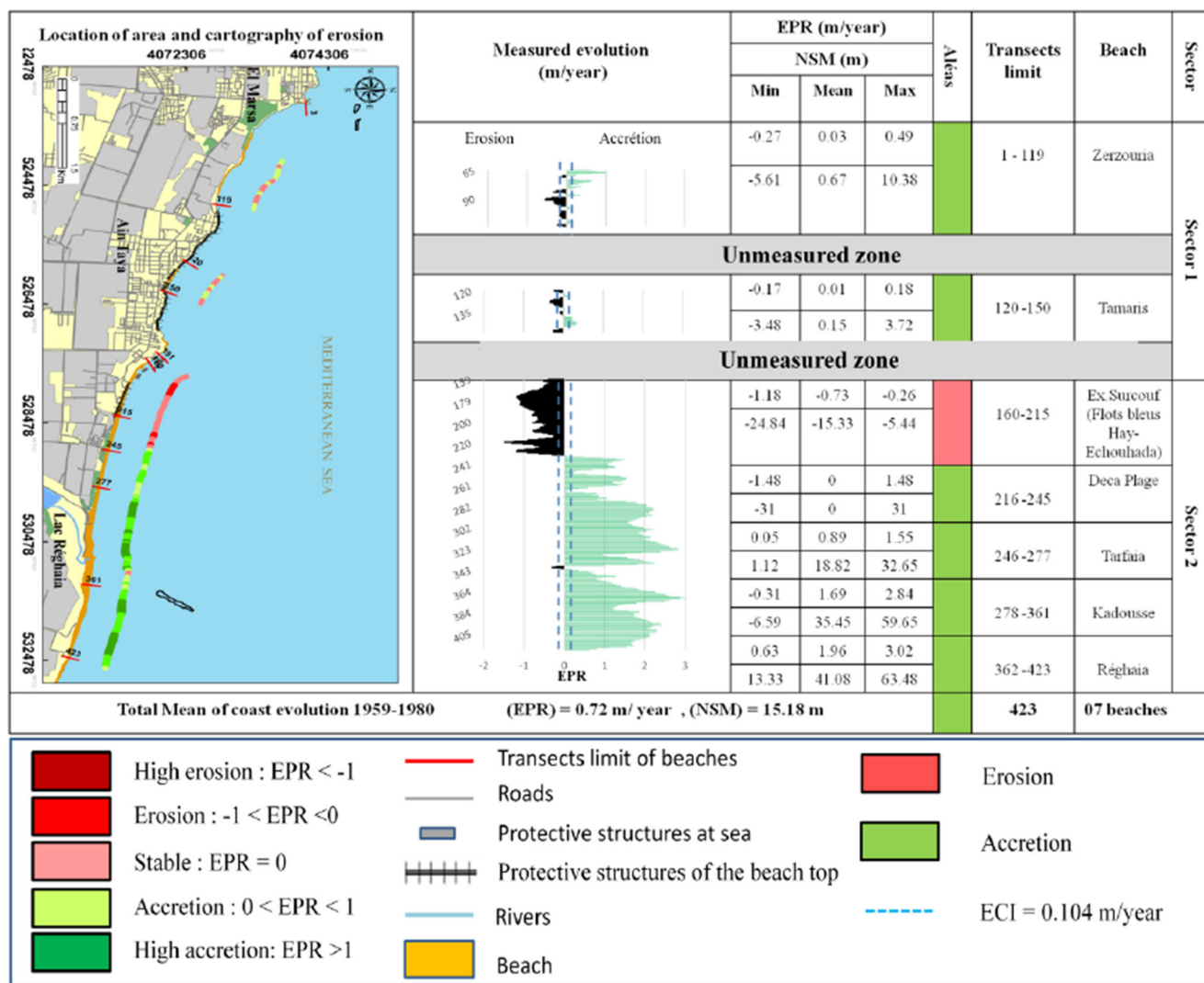
**Table 4** Gained and lost surfaces along the east of Algiers (NSBS: number of the Surface Balance Sheets)

Beaches	1959–1980			1980–2003			2003–2017			1959–2017			
	Gain (ha)	Loss (ha)	NSBS (ha)	Gain (ha)	Loss (ha)	NSBS (ha)	Gain (ha)	Loss (ha)	NSBS (ha)	Gain (ha)	Loss (ha)	NSBS (ha)	
Zerzouria	1–119	0.10	-0.10	0.00	0.57	-0.01	0.56	0.05	-3.30	-3.25	0.09	-1.81	-1.72
Tamaris	120–150	0.05	-0.06	-0.01	0.51	-0.14	0.37	0.00	-1.25	-1.25	0.00	-0.81	-0.81
Surcouf	160–215	0.00	-1.75	-1.75	0.00	-1.07	-1.07	0.31	-0.96	-0.65	0.02	-3.48	-3.46
DecaPlage	216–245	0.05	-0.63	-0.58	0.14	-0.60	-0.47	0.11	-0.51	-0.40	0.13	-1.04	-0.92
Tarfaia	246–277	0.35	0.00	0.35	0.09	-0.67	-0.58	0.20	-0.45	-0.25	0.58	-0.20	0.38
Kadousse	278–361	1.52	-0.03	1.49	0.18	-1.39	-1.20	1.35	-0.33	1.02	5.77	0.00	5.77
Réghaia	362–423	1.29	0.00	1.29	0.28	-0.46	-0.17	0.28	-0.51	-0.23	4.25	0.00	4.25
Total		3.35	-2.56	0.79	1.77	-4.33	-2.56	2.31	-7.32	-5.02	6.58	-3.09	3.49

movement of the Reghaia River mouth towards the beach of El Kadouss in 2008 led to a degradation of the El Kadouss dune. Sediment reserves have been disrupted; thus, the impact has been very apparent in the last few years.

**Period from 1959 to 1980**

As depicted in Fig. 4, for this period (1959–1980), an average EPR of +0.72 m/year and an overall NSM of 15.18 m are



**Fig. 4** Statistical synthesis of coastline kinematics and coastal erosion mapping in the period of 1959–1980 on the eastern coast of the Algiers



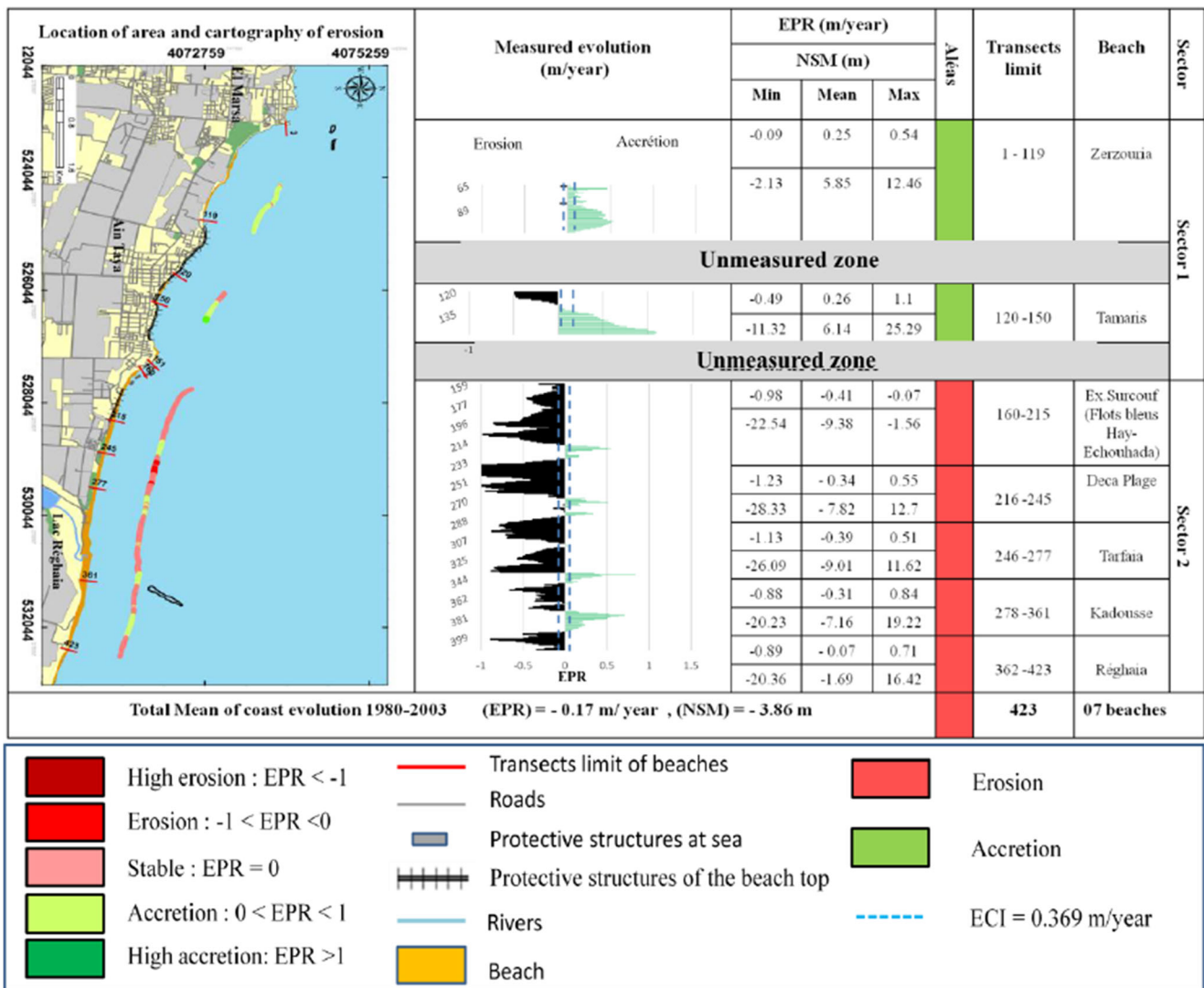


Fig. 5 Statistical synthesis of coastline kinematics and coastal erosion mapping in the period 1980–2003 on the eastern coast of the Algiers

observed. These values show that the zone has a strong accretion in some sectors; additionally, the Surcouf Beach is subjected to strong erosion. The western sector presents a stability that can be qualified as natural, and the Zerzouia cliffs and Tamaris Beach seem to have stable evolution (very low EPRs). This can be explained by the lithology of this zone (Bouhamadouche 1993) as well as the absence of consistent forms of protection that could induce a change in the sedimentary dynamics in this sector.

Similarly, in sector 2 for the same period, Surcouf Beach, when exposed to high wave energy, showed an apparent recession that recorded a maximum rate (EPR = - 0.73 m/year). This reflects the high degree of vulnerability in this part of the study area. The beaches of the eastern extremity are experiencing an important accretion due to their dissipative character, which favours the deposition and accumulation of sediment. El Kadouss Beach records the maximum EPR of 1.69 m/year. However, in this zone, a slight form of erosion

occurs, which is probably due to natural movements of the Reghaia River mouth (Fig. 8e).

### Period from 1980 to 2003

Overall, an average EPR of - 0.17 m/year and an NSM of 3.86 m are observed. Such values attest to the severe erosion that the area has undergone (Fig. 5). The hypothesis of the intervention of coastal drift, which conforms to the main wave direction in the transport of sediment from sector 02 to sector 01, is not excluded.

During this period, sector 01 has always had a relative stability or even accretion that translates into equivalent EPRs of approximately 0.25 m/year on all the beaches. This may be due to the natural cycle of sediment deposition and beach formation at the foot of the sea cliffs in accordance with the classical sediment dynamics scheme. Additionally, sector 02 experienced dramatic erosion. The Surcouf, Tarfaia and El

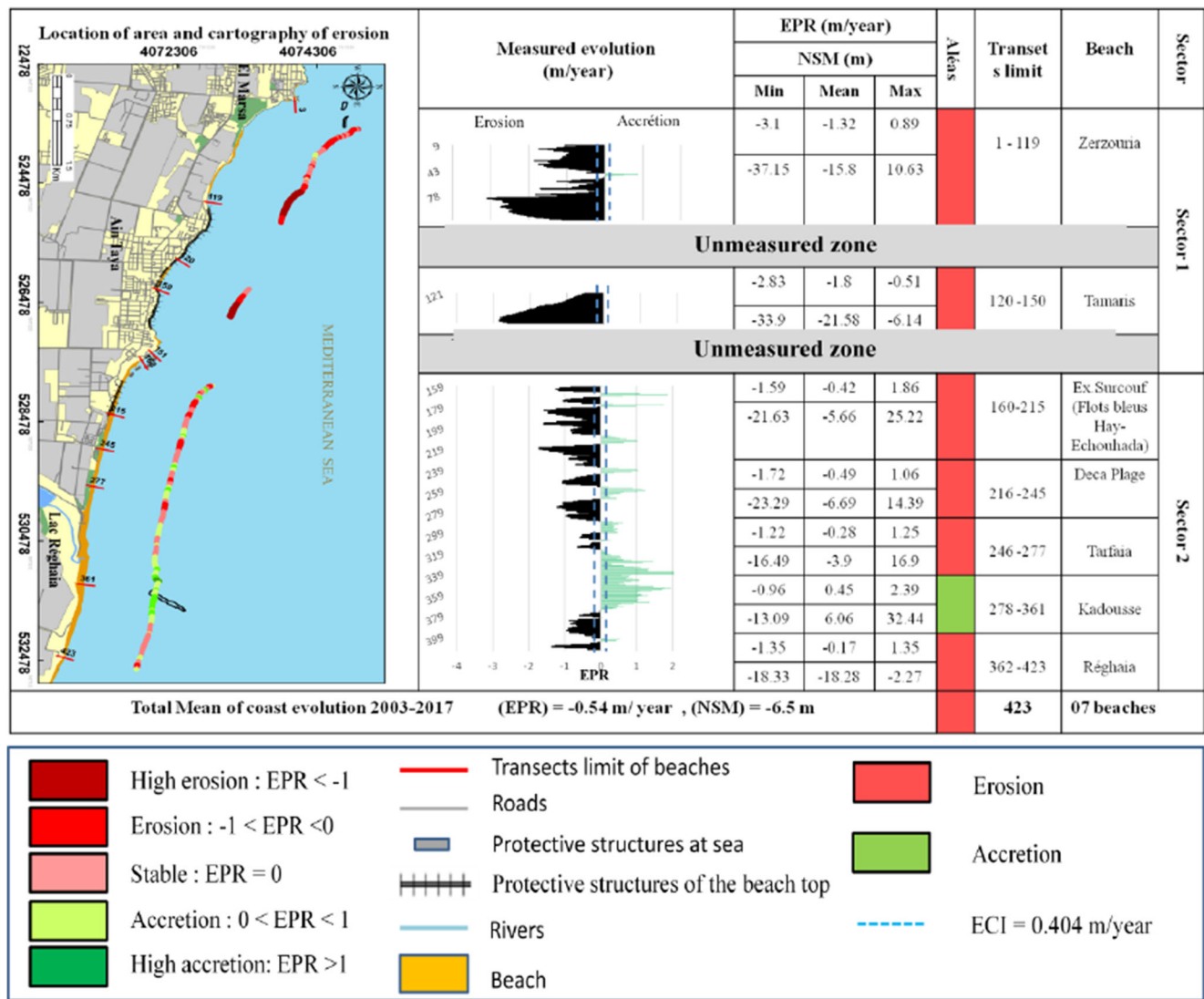


Fig. 6 Statistical synthesis of coastline kinematics and coastal erosion mapping in the period of 2003–2017 on the eastern coast of the Algiers

Kadousse beaches have the maximum retreats with average erosion rates of  $-0.41$  m/year,  $-0.39$  m/year and  $-0.31$  m/year, respectively. Hydrodynamic and degradation of the dunes during this period seem to be the main reasons governing this phenomenon.

### Period from 2003 to 2017

During this period, a rapid negative evolution is observed with an EPR of  $-1.32$  m/year and  $-1.8$  m/year for the Zerzouria and Tamaris beaches, respectively. The expansion of urbanization has led to an increase in the stakes to protect the properties in the coastal zone, as was the case following the storm events of 2007. For this purpose, the recordings of the ONM at its stations (Algiers-eastern region) allowed us to detect a significant number of storms that strongly influenced the evolution of this zone.

Generally, these defence structures have had a major impact on sediment transport involving the formation of accumulation surfaces, causing a deficit in the sedimentary budget and accentuating erosion in parts of the adjacent areas. The average EPR for this period is  $-0.54$  m/year, and the NSM is  $-6.5$  m. These results (Fig. 6) are consistent with a recent study in the area by Bounoua et al. (2017), who confirm the high vulnerability and erosion that the area faces.

Similarly, a punctual accretion on the beaches of sector 02 is noticed in the area of protection infrastructures (Fig. 8d), which are located in the Les Flots bleus and Hay Echouhada sections of Surcouf beaches. However, these structures do not succeed in reducing or stabilizing the negative trend in the western part of this sector, where an EPR of  $-0.42$  m/year is noticed (Fig. 8d).

The same can be said for the Decaplage, Tarfaia and Réghaia beaches, where the ERPs are  $-0.49$  m/year,  $-0.28$  m/year and  $-0.17$  m/year, respectively. It should also

**Fig. 7** Surface evolution of El Kadouss dune ridge between 2006 and 2012



be noted that El Kadouss Beach, which is located between the two beaches of Tarfaia and Reghaia, presents an accretion of the shoreline up to +0.45 m/year. This is due to the presence of the dune, thus reducing the rate of erosion by compensating the sediment for this beach and for the two adjacent beaches.

### Surface sediment budget

Table 4 represents all the gained and lost surfaces along the study area. In fact, to allow a vision of the coastal evolution, measurements of shoreline changes and calculation of surface sediment budget were combined (Kermani et al. 2016). According to Table 4, the total beach area lost during the period 1959–2017 is 11.59 ha, with the exception of the El Kadouss and Reghaia beaches located at the eastern part of the coast, which exhibited a gain of 10.83 ha. This balances out for the area as a whole, but overall still has a net loss.

The results in Table 3 confirm the dynamic evolution change between the periods. Beaches appear steady with little accretion during the period of 1959–1980. This state started to change during the period of 1980–2003, where land loss became significant (−2.56 ha). During the last period (2003–2017), a massive loss of land reaching 5.02 ha is noticed. The maximum loss that occurred during this period was approximately 7.32 ha.

### Discussion

This study has shown that except for some areas (Reghaia River mouth), both sectors are subjected to an erosion risk where the evolutionary trend of the coastline is in recession in recent years. Indeed, Table 3 shows that the evolution of the

coastline fluctuates over time, and the coastline was overall in accretion from 1959 to 1980 (69% accretion vs. 31% erosion). This evolution has completely changed in the second period; from 2003, a complete inverse of trend is noticed, with 31% accretion vs. 69% erosion.

The results in Tables 3 and 4 show that the total beach area lost during the period 1959–2017 amounts to an area of 3.09 ha. Currently, the zone presents a tendency towards erosion. This tendency obviously has driving factors; in fact, the eastern zone of the Algiers is characterized by very attractive nature and a geomorphological diversity (wide beaches, cliffs, wetlands and islands), subjecting it to a permanent development pressure. According to PAC (2012) and Touati (2012), pressure from economic development will generally result in accelerated urban dynamics. For the Algiers region, these pressures are characterized by the littoralization of the population and activities that have increased significantly.

During its evolution, the eastern coast of Algiers has experienced an unprecedented transformation, especially an expansion of the local construction industry to cater to the needs of different sectors: dwelling, industry and tourism. These anthropogenic actions have caused alteration and transformation of coastal landscapes; therefore, the likelihood of increased coastal hazards has been multiplied. Rabehi et al. (2018) declared that “physical characteristics of the coast” have the most influence on the calculation of indicators of vulnerability. These authors also add that in Algiers, causes of anthropogenic origin seem to dominate the phenomenon, which shows that coastal geomorphic stability varies significantly according to the local specifics of the regions studied.

It is also worth noting that the beaches of eastern Algiers are exposed to multiple natural factors unfavourable to their accretion. The areal configuration and orientation are very



favourable to hydrodynamic attacks (Fig. 8c), particularly from the North-West storm swells (Bengoufa et al. 2016). Field observations show that the vulnerable lithology of some parts of the studied zone can create a recession state in the western zone.

The overcrowded beaches, the abusive extraction of sand shown in Fig. 8i, the illegal mechanical sports, the reorientation of the Reghaia River mouth and the closing of the valve that separates the Reghaia River from the lake, are the anthropogenic actions that have strongly disturbed the sediment

supply on the beaches (Fig. 7). This led to the deficit of the sediment carried by the Reghaia River and to the strong degradation of the El Kadouss dune, which has always been a natural protection against wave attacks.

Reghaia beach erosion may be due to the massive and arbitrary removal of quantities of sand required for urban development experienced by the area of Algiers. This led the authorities since the 1970s to unlock several sand extraction sites along the eastern coast of Algiers (CAR/ASP-PNUE/PAM 2015). These extractions simultaneously affected the



**Fig. 8** a–d Surcouf beach before, during and after storm. e The mouth of Reghaia-river. f Cliffs of Zerzouria. g El Kadouss dune ridge after restauration. h The pasture practiced by the cattle. i The sand extraction traces. j El Kadouss dune ridge after storm



riverbeds, beaches and dune ridge. Although extraction is currently prohibited, some cases have been observed during investigations (Fig. 8i). Additionally, the relative rise in sea level (0.2 m/100 years) can increase the impact of repeated storms (GIEC 2014). In addition, the comparative study of the dune contours for 10 years (2006–2016) carried out by Bounoua et al. (2017) showed that the Kadouss dunes have undergone a surface reduction of approximately 0.37 ha (Fig. 9).

Moreover, according to the study of storms by the National Office of Meteorology (ONM 2015), during October 2017, a storm occurred with an average speed of 14.33 m/s and caused a regression of the dune ridge of 28.07% (Fig. 8j). Local authorities realized this issue, resulting in the initiative to restore the dune by a flexible method in September 2015. This restoration showed some effectiveness (Fig. 8g), but cattle grazing in the pasture (Fig. 8h) produced a new degradation of the dune.

Otherwise, the protection infrastructures (Fig. 8d), which were installed since 2009 in Flots Bleus, did not succeed in reducing the negative trend. In contrast, this type of hard protection structure has caused a change in the hydro-sedimentary operation in the area. Different approaches can be favourably accepted by decision-makers and communities. Nonetheless,

they are far from being considered as an ultimate solution (Bartolini et al. 2018).

The study of the coastline kinematics is effective for developing a pragmatic approach, from field observations to the use of geospatial techniques with a geographic information system (DSAS extension). This study has allowed us to formalize, characterize (calculation of EPR and NSM), qualify (strong or weak) and finally map coastline kinematics, with a perspective that can be quantitative by using these data to predict coastal vulnerability.

Based on the calculation of the coastal vulnerability index CVI, Rabehi et al. (2018) state that the towns described as vulnerable are characterized by the presence of numerous protective structures against coastal erosion. The study of Mihoubi et al. (2014) supports the statement of Rabehi et al. (2018) which evaluated the high vulnerability of the eastern areas of the Algiers region through the application of CVI (McLaughlin and Cooper 2010). Nationally, the recent application of CVI in Bejaia Bay (Djouder and Boutiba 2017) also shows increased coastal vulnerability due to demographic pressures which usually go with an important anthropisation. Assessing the degree of coastal vulnerability allows to assist



**Fig. 9** a, b The valve of separation between the Reghaia River and the Reghaia lake (sediment trapping). c, d Deviation of the Reghaia mouth river. e Seawalls installation in Ain Taya

decision-makers for considering coastal erosion when updating municipal and regional development plans (POS, PDAU). This would enable a preliminary selection of the most vulnerable communes (Duriyapong and Nakhapakorn 2011).

## Conclusions

The purpose of this study was to evaluate the evolution of the shoreline of eastern Algiers during the period 1959–2017; it showed that although the global surface balance remained positive with accretion of  $3.4 \pm 0.09$  ha, a trend of erosion was reported with a loss of more than  $7.3 \pm 0.02$  ha during the previous few years.

The diachronic analysis, especially between the periods of 1959–1980 and 2003–2017, revealed a reversed trend in the overall coastline evolution, which was positive until 2003. Since then, rapid and severe erosion has been observed along almost all beaches.

This work revealed that Surcouf Beach is the most vulnerable sector in the area, with an estimated loss of 0.6 m/year. El Kadouss Beach remains the most protected sector with a gain of almost 0.6 m/year; this is due to the natural protection provided by its dune ridge, although these dunes are threatened. The Reghaia Beach, for its part, showed an alarming evolution during the last decade.

This paper shows that the merging of geospatial techniques such as aerial photographs and DGPS data using GIS software can provide reliable and valuable information on coastal evolution. Additionally, the use of the DSAS geostatistical computing tool has given satisfying results, which are very consistent with the observations and the reality in the field. The coastal monitoring carried out in this study can assist and support decision-making for an integrated coastal zone management (ICZM) and for the management policy undertaken in the Algerian coastal zone.

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