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Environmental Earth Sciences

ISSN 1866-6280
Volume 71
Number 3

Environ Earth Sci (2014) 71:1213-1225
DOI 10.1007/s12665-013-2525-6

Springer

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ORIGINAL ARTICLE

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Received: 23 October 2012 / Accepted: 25 April 2013 / Published online: 14 May 2013

Abstract The short and medium-term coastal evolution of Necochea Municipality, Buenos Aires province (Argentina) was studied. The medium-term evolution study was based on aerial photographs from 1967 and 1984, and satellite images from 2004, using the dune or cliff toe as coastline indicator. The short-term evolution was studied from February 2006 to December 2009 by means of seasonal beach profiles and sediment sampling. Results showed that in the medium-term at Necochea, the coastline has remained stable or has advanced. Whereas in the short-term, the analysis has evidenced incipient erosion processes. On the other hand, at Quequén the retreat of the coastline and the negative sedimentary balances (medium and short-term) are clearly indicating an accentuated erosion process. The different degrees of coastal erosion are related in part to beach vulnerability to wave storms but mainly to anthropogenic actions, which have affected the beach sediment supply. These results evidence the necessity to develop a coastal management programme.

Keywords Coastal evolution · Beach profile · Coastline · Necochea · Quequén

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Introduction

Sandy beaches exhibit a wide range of variability along the coast in different temporal and spatial scales (Esteves et al. 2006). These changes are the result of multiple elements and processes that interact or act individually. Therefore, beaches and coasts manifest morphological changes in short, medium and long-term, as well as episodic changes. All of these changes can be studied by a wide variety of methods according to the time and spatial scales considered (Anfuso et al. 2007a). Those studies that consider periods of 10–60 years or more than 60 years constitute, respectively, medium and long-term studies (Crowell et al. 1993; Boak and Turner 2005). Aerial photographs, satellite images and historical maps are the most often used data source (Allan et al. 2003; Domínguez et al. 2005; Forbes et al. 2004; Anfuso et al. 2007a; Lorenzo et al. 2007; Martínez del Pozo and Anfuso 2008; El Banna and Frihy 2009). In Argentina, few studies have been done to determine the coastline position in urban centers. Analyses of the coastline advance/retreat in these studies have shown temporal and spatial variability. Therefore, the search for the causes of these erosive processes is a complex task (Isla et al. 1998; Del Río et al. 2007; Merlotto and Bértola 2009).

A series of physical features can be used as coastline indicators on aerial photographs (Pajak and Leatherman

2002). Among these, the dune or cliff toe is considered a appropriate coastline indicator for medium-term changes and has been employed in different studies in Argentina (Isla et al. 1998; Marcomini and López 1999; Merlotto and Bértola 2009) and Spain (Domínguez et al. 2005; Anfuso et al. 2007b) to cite some examples. To estimate the rate of coastline change, the end point rate method has been historically used (Dolan et al. 1991; Allan et al. 2003) and is still valid (Forbes et al. 2004; Morton et al. 2005; Anfuso et al. 2007a; Merlotto and Bértola 2009). This method contributes to reduce the effect of seasonal changes (summer/winter) and the influence of a single storm (Anfuso et al. 2007a).

Short-term studies involve periods shorter than 10 years (Crowell et al. 1993). In these, the most common method used to evaluate the dynamics and evolution of the beaches is the periodic execution of topographic profiles (Anfuso et al. 2007a; Taaouati et al. 2011). The study of the changes in sand volumes and physical features of a beach, contribute to the understanding of the causes that generate these changes and erosive process. Based on a better understanding of these processes, prevention and mitigation measures can be formulated. Anfuso et al. (2006) estimated, for North African beaches, that the morphological and volumetric changes are more related to frequency and intensity of storms than to the seasonal cycle behavior. Masselink and Pattiaratchi (2001) found that in beaches in West Australia seasonal changes are better explained by a seasonal reversal in the littoral drift direction than by variation in the incident waves. In Buenos Aires province, Argentina, storm surges and wave storms are the main cause of natural coastal erosion (Pousa et al. 2007), and together cause an important deterioration and destruction of coastal infrastructure (Bértola 2001; Pousa et al. 2007; Merlotto and Bértola 2009). Nevertheless, diverse studies have shown that neighboring beaches can present different erosion/accumulation cycles (Isla et al. 2001; Bértola et al. 2009). Marcomini and López (1997) observed erosive cycles in Villa Gesell during spring–summer due to high storm frequency, while in autumn–winter they recorded deposition.

The area considered in this contribution is located in the south of the province of Buenos Aires and it includes the localities of Necochea and Quequén (Fig. 1). The cities are separated by the Quequén Grande River and the Quequén Port. The harbor is flanked by two breakwaters, of which the longest is the southern one with a length of 1,600 m. The study area sits on fields of coastal dunes fixed by different degrees of vegetation. The dunes are located mostly upon brownish silt cliffs. There are also inactive cliffs partially or totally covered by dunes. The presence of sand ramps is important as well as active cliffs. The predominant wind directions are N and NW (Merlotto and Piccolo 2009). The prevailing littoral drift is SW–NE coinciding with the coastal orientation. Tide is mixed, mainly semidiurnal with a mean amplitude of 0.98 m and maximum amplitude of 1.85 m (SHN 2009).

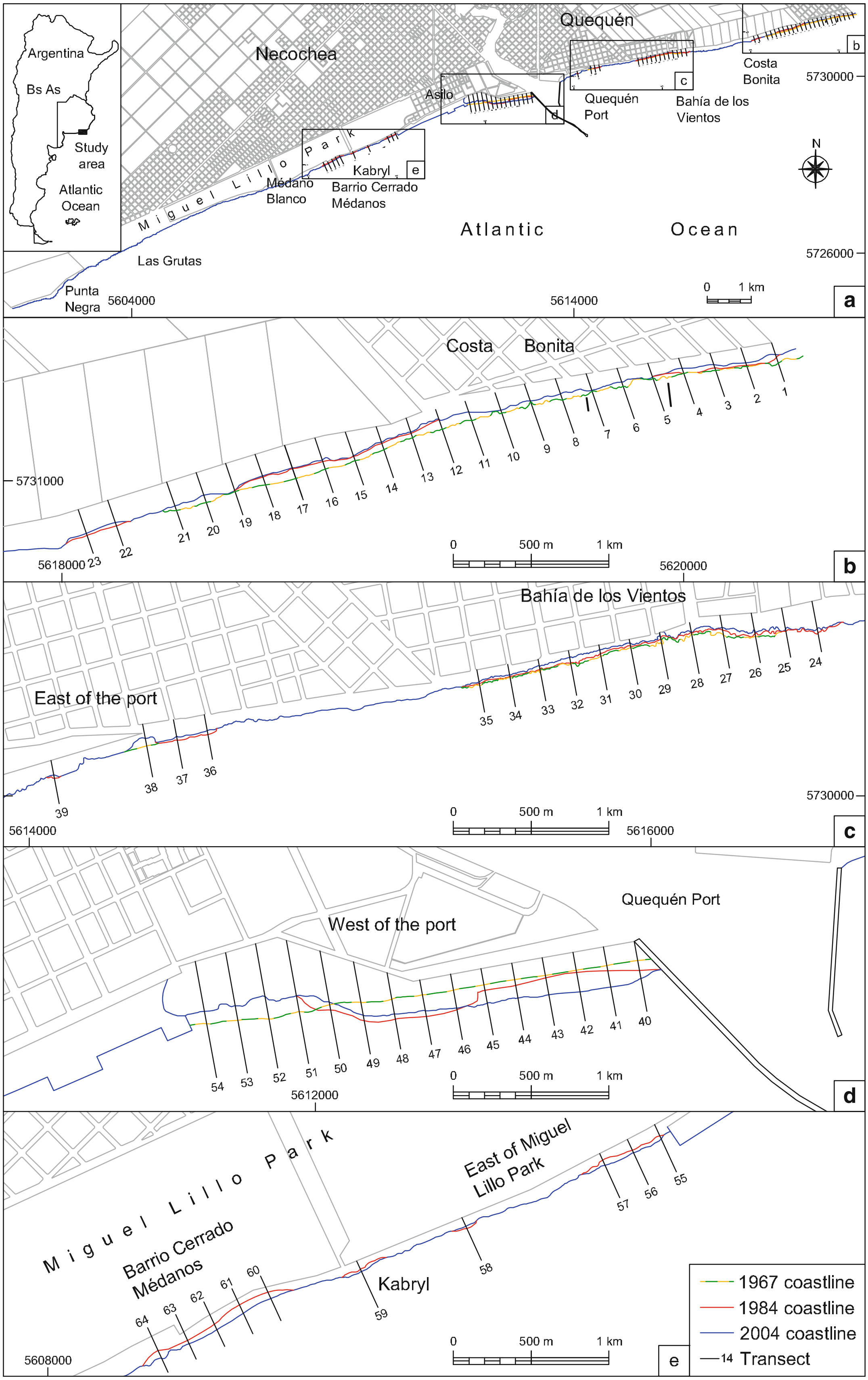
Fig. 1 Location of the study area and coastline position in 1967, 1984 and 2004. **a** Study area and location of the sectors with changes in coastline position, **b** Costa Bonita Beach Resort, **c** East of Quequén Port and Bahía de los Vientos (Quequén City), **d** West area of Quequén Port (Necochea City) and **e** Coastal front of Miguel Lillo Park

The development of the harbor and the urban growth of the cities have altered the landscape and its natural dynamics. This is mainly due to the fixation of the dune fields and the construction of the breakwaters of the port. These retain sediments transported by littoral drift and form sandbanks at the ports mouth, affecting beach supply (Isla et al. 2009) and causing coastal erosion in Quequén. In this paper the short and medium evolution of the coastal urbanized sector of the Necochea Municipality was analyzed. The short-term evolution was evaluated studying the morphological, volumetric and grain size variability of the beaches; while the medium-term evolution was assessed based on the historical coastline position.

Materials and methods

To determine the coastline evolution of the study area (Fig. 1) a map adjusted to the topographic sheets N° 3960-12-4 and N° 3960-12-3 y 18-1 of the Instituto Geográfico Nacional (IGN) at a 1:50,000 scale was constructed. The map was elaborated based on the digital land registry map of the cities of Necochea and Quequén using mapping software. The sources of data used to determine the historical coastline were vertical aerial photographs from the years 1967 (scale 1: 20,000, INTA) and 1984 (scale 1:20,000, Dirección de Geodesia de la Provincia de Buenos Aires), and Quickbird satellite images from 2004 (Google Earth®: 2.5 m spatial resolution). Aerial photographs and historical maps were digitized with a high resolution scanner (1,200 dpi) and georeferenced from a minimum of 15 control points in the Gauss Krüger flat coordinates system. The control points were verified among the different sources used.

Different authors have analyzed the potential errors associated to the aerial photographs and to the measuring procedures (Anders and Byrnes 1991; Crowell et al. 1991). In this study, errors due to distortions of the photographs have been minimized following the explicit suggestions of these authors. Furthermore, by using the dune or cliff toe as the coastline indicator, variations in the position of the coastline due to seasonal effects and meteorological conditions of the days prior to the taking of the photographs


Argentina
Bs As
Study area
Atlantic Ocean
Necochea
Quequén
Asilo
Quequén Port
Bahía de los Vientos
Costa Bonita
Miguel Lillo Park
Kabryl
Médano Blanco
Barrio Cerrado Médanos
Las Grutas
Punta Negra
Atlantic Ocean
N
5730000
5726000
5604000
5614000
0 1 km
a
Costa Bonita
5731000
5618000
5620000
0 500 m 1 km
b
Bahía de los Vientos
East of the port
5730000
5614000
5616000
c
Quequén Port
West of the port
5612000
d
Miguel Lillo Park
Barrio Cerrado Médanos
East of Miguel Lillo Park
Kabryl
5608000
e
1967 coastline
1984 coastline
2004 coastline
14 Transect

are reduced. Finally, comparing aerial photographs distant in time in an area where coastline changes are large, the error will be small in relation to those changes (Crowell et al. 1991). Therefore, the rates obtained are considered highly reliable.

The dune or cliff toe lines of the mentioned sources were digitized to obtain a map of the coastline evolution. In the sectors where coastline changes where verified, perpendicular transects to the coastline were plotted every 200 m. Operator errors can induce incorrect results so care was taken during the measuring procedure. Geometric data between the dune or cliff toe for all the lines were conducted, obtaining the advance/retreat rates between each period by the end point rate method. It calculates the coastline displacement between the earliest and most recent shorelines, but if several coastline positions are available, combination of rates can be calculated (Dolan et al. 1991). The main disadvantage of this method is that available data is not used in the analysis, and using only two data points, important trends or changes in trend may not be detected (Dolan et al. 1991).

The morphological monitoring of the beaches was carried out by seasonal beach profiles surveyed from February 2006 to December 2009. Profiles were taken from a fixed position (station point) extending to a depth of approximately 0.5 m below the low tide level. Measurements were taken every 5 m using a theodolite (Nikon NT2A). The beaches studied are, from East to West, Costa Bonita (CB) and Bahía de los Vientos (BV) in Quequén; and Asilo (A), Kabryl (K) and Médano Blanco (MB) in Necochea (Fig. 1). At CB, three beach profiles were made spaced 100 m apart and referenced to the topographic zero level (IGN). In each of other beaches one profile was constructed, and since it was not possible reference any of them to the IGN level, they were referenced to a relative height.

The analysis of the field data allowed the reconstruction of the beach morphology. Total and foreshore beach slopes, sediment volumetric variations between surveys and final sedimentary balance were calculated. For the latter, the Fox and Davis (1978) method was used since it has been widely used in the study of the beaches in Buenos Aires province (Isla et al. 1998, 2001, 2009; Bértola 2001; Bértola et al. 2009). The unitary volumes of the profiles were calculated using the following equation:

$$V_2 = H_2 \cdot 5 \cdot 10$$

where V_2 and H_2 are the volume (m^3) and height (m) of the second point or measurement of the profile, respectively. Five meters is the distance between measurements and 10 m is the extrapolated distance considered as the lateral continuity of the profile (5 m to each side of the measurement). For the first and last points, a distance of 2.5 m was considered to the next measurement. To obtain the volume of each profile the unitary volumes were summed. The eroded/accumulated volumes between two consecutive surveys were obtained from:

$$V_{fe} = \Sigma(V_{1f} - V_{1e}) + (V_{2f} - V_{2e}) + \cdots + (V_{nf} - V_{ne})$$

where V_{fe} is the eroded/accumulated volume between the period f to e, being f and e, the dates of the surveys. Consequently the final sedimentary balance or the total eroded/accumulated volume during the considered period is:

$$Vt = \Sigma V_f + V_e + \cdots + V_n$$

In most cases beach profiles with different length were compared. In each comparison the length of the shortest profile was considered. The length of the beach profile (beach width) is the distance between the station point and the last measurement under the low tide level. The total and foreshore beach slope (in percentage) was obtained from:

$$P = (C_1 - C_f)/L \cdot 100$$

where C_1 is the height of the first point in the profile and C_f the last. L is the distance between both points. To obtain the foreshore slope the difference in height and distance between the berm crest and the last point were considered. Later, the geomorphology and the volumetric changes of beaches were related to the wave storms that occurred during the considered period.

Wave data were obtained from the Interocean wave gauge model S4 AWI (Quequén Port Management), for the period July 2006–December 2009. The wave gauge is located 400 m southwest of the south breakwater of the port. A significant wave height of 1.5 m was considered for storm waves while extreme storm waves were considered with a wave height of 2.5 m (Merlotto et al. 2010).

During the surveys, a sedimentary sampling along the beach profiles was conducted. Representative superficial samples were collected from foreshore, backshore and dune sub environments. Sediment samples were processed in the laboratory. The sediment samples were sieved using a Ro-Tap sieve shaker for 15 min through 10 or 15 sieves (according to the sample grain size), ASTM norm every 0.5 phi interval. Statistical parameters were calculated (Folk and Ward 1957) by GRADISTAT software (Blott and Pye 2001).

Results

Coastline evolution

The coastline from Costa Bonita to Punta Negra has suffered significant advances and retreats in its position, at different locations, between 1967, 1984 and 2004 (Fig. 1a). The areas affected by retreat are Costa Bonita, Bahia de los Vientos and East of the Quequén Port. Coastline advance processes were observed only at Necochea: next to the port, in the east sector of Miguel Lillo Park, in the seaside resort Kabryl and in the gated community Barrio Cerrado Médanos.

During the period 1967–2004 the area of Costa Bonita was the most affected by erosion (Fig. 1b), with a mean retreat of the coastline of 18.59 m at a 0.5 m/year rate. The transect 17 was the most affected (−35.72 m) while transect 19 (−3.88 m) was the least affected by erosion. In Bahía de los Vientos (Fig. 1c), the coastline retreated 17.02 m (0.46 m/year) with a maximum value in transect 29 (−37.45 m) and a minimum in transect 25 (−7.01 m). The East of the port registered a shoreline retreat of 14.9 m. Globally, the coastline at Quequén retreated 16.84 m (Table 1), with 0.1–1 m/year rates depending on the sector.

Necochea registered accretion processes during the period 1967–2004. The coastline advanced 15.55 m at a mean rate of 0.42 m/year (Table 1). The area West of the port (Fig. 1d) experienced the highest shoreline advance (0.65 m/year) though some transects registered a retreat of the dune toe line. The advance of the coastline in front of Miguel Lillo Park (Fig. 1e) experienced the lowest mean annual rates, and at the community gated Barrio Cerrado Médanos the rates arose to values close to those of the area West of the Port (Table 1).

Considering the evolution of the coastline in each period studied, the most erosive process in Quequén (−0.54 m/year) was registered during the 1967–1984 interval, and the most affected area was Costa Bonita (−0.86 m/year) (Table 1). In Necochea, only the west of the port experimented coastline variations (Fig. 1d, e). The dune toe advanced from transects 40–50 (11.08 m/year) and retreated from transects 51–54 (−0.65 m/year). During the period 1984–2004, the erosive process decreased a 75 % (Table 1) at Costa Bonita. Some sectors did not register changes (transect 5–11) while the east sector experienced a significant increase in the rates (Fig. 1b). At Bahía de los Vientos the retreat of the coastline doubled, while the sector East of the port registered a slight increase in the erosion rates. At Necochea, in the area West of the port the coastline advance continued at the same rates as in the previous period. Also, the coastline advanced in front of Miguel Lillo Park (Fig. 1e). The mean rate was 7.9 m/year in the east, while in the west (Kabryl and Barrio Cerrado Médanos) the rates were higher (22 m/year) (Table 1). Transect 58 was the only one that registered coastline retreat (7.1 m) (Fig. 1e).

The remainder coastline of the study area toward the west to Punta Negra did not register changes. Sandy beaches of diverse width develop almost uninterruptedly at the toe of the cliffs. Although the presence of active cliffs with rocky shore platforms and other features (sea caves, rock slides, collapsed rocks) from Las Grutas to Punta Negra (Fig. 1a) indicate marine abrasion, the coastline has been stable since 1967, since these physical features have been identified in the different sources analyzed.

Wave characteristics

The annual distribution of significant wave heights during 2006–2009 (Fig. 2) evidences that the higher values occur during winter (1.26 m) followed by autumn and spring (both with 1.18 m), and lastly summer (0.96 m). The mean annual significant wave height is 1.14 m.

Regarding the number of days with storm waves (Hs ≥1.5 m) the pattern is similar in winter and autumn.

Table 1 Coastline advance or retreat in the studied area for each period and year analyzed

Area	1967–1984		1984–2004		1967–2004	
	m/period	m/year	m/period	m/year	m/period	m/year
Quequén						
Costa Bonita	−14.56	−0.86	−4.04	−0.2	−18.59	−0.5
Bahía de los Vientos	−6.7	−0.39	−10.32	−0.52	−17.02	−0.46
East of the port	−6.31	−0.37	−8.59	−0.43	−14.9	−0.4
Mean	−9.19	−0.54	−7.65	−0.38	−16.84	−0.46
Necochea						
West of the port	11.08	0.65	12.98	0.65	24.06	0.65
East of Miguel Lillo Park	0	0	7.9	0.4	7.9	0.21
Kabryl	0	0	8.23	0.41	8.23	0.22
Barrio Cerrado Médanos	0	0	22	1.1	22	0.59
Mean	2.77	0.16	12.78	0.64	15.55	0.42

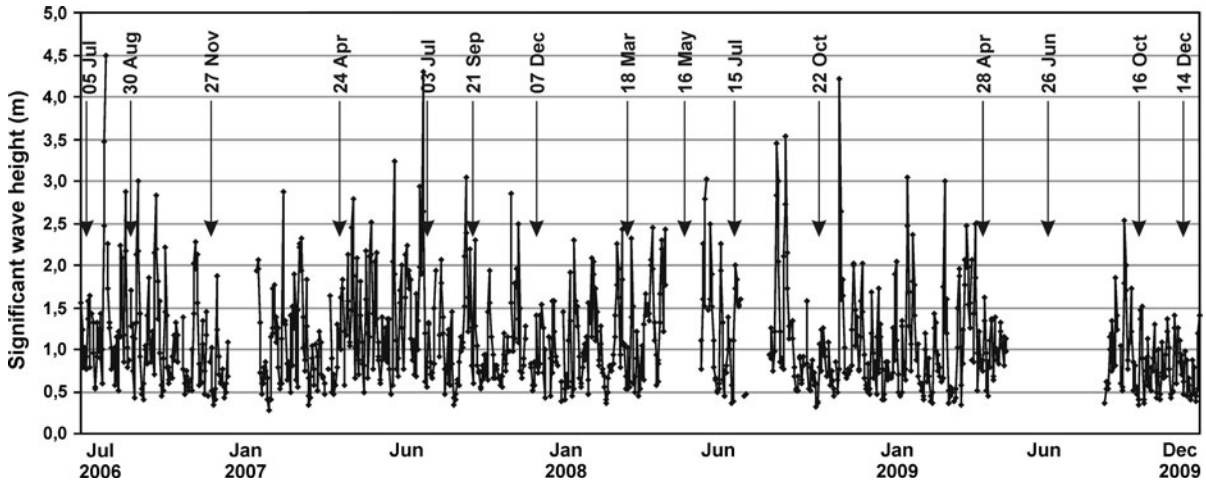


Fig. 2 Distribution of the mean daily significant wave height between July 2006 and December 2009 and field surveys

Almost 25 % of the days the significant wave height is superior to 1.5 m. The major frequency in severe storm waves (Hs ≥2.5 m) is observed in winter followed by spring (3.5 % days).

Grain size characteristics

Grain size characteristics are different in both localities of the study area. Foreshore sediments of CB correspond to poorly sorted coarse sand. Of the samples, 54 % were bimodal or polymodal, corresponding to very fine to medium gravelly coarse sand. The backshore is composed of moderately well-sorted medium sand. The foredune is composed of well-sorted fine sand. Due to the temporal variability in mean grain size registered at the CB beach, it is considered as mixed sand and gravel beach. Fore and backshore sands from BV are very similar. They are moderately well-sorted medium sands.

The beaches in Necochea present similar grain size characteristics. There is also a high similarity between sampling points of each profile. The sediment from fore and backshore, and foredune in A, K, and MB, corresponds to well- or very well-sorted fine sand (Table 2).

Table 2 Statistical parameters mean and sorting (phi) of the sediments

Beach	Foreshore		Backshore		Dune	
	Sorting	Mean	Sorting	Mean	Sorting	Mean
CB	1.043	1.043	0.632	1.823	0.451	2.145
BV	0.585	1.765	0.529	1.772	–	–
A	0.384	2.213	0.423	2.206	–	–
K	0.421	2.147	0.378	2.4	0.362	2.48
MB	0.42	2.218	0.415	2.335	–	–

Morphological and volumetric variations

Costa Bonita beach (CB) (Fig. 3a) develops between a rocky shore platform and a coastal dune. It registered a negative sedimentary balance (-241.2 m^3) during the whole period studied (Table 3). Although erosive cycles were dominant, alternate erosion–deposition cycles were observed. During spring–summer the volumes eroded ranged from -12.3 to -90 m^3. The depositional periods were registered in autumn and winter of 2006 and 2009 with mean values ranging from 8.6 to 34 m^3 (Table 3). Different cycles in the volumes involved or in the type of cycle (erosive or accumulative) were verified among the three profiles. The southern profile (Fig. 4a) presented a sedimentary balance mainly linked to wave storm events (Fig. 2); while in the northern profile (Fig. 4c), these events had less influence. In some cases, while erosion was registered in the southern profile, sand was deposited in the others, evidencing longshore sediment transport. It is estimated that the groins next to the central and northern profiles (Fig 4b) retain part of the sediment that is removed from the southern profile. However, the final sedimentary balances of the northern and southern profiles were negative. The beach slopes at CB are medium to steep (Table 4). The southern profile presented lower and more uniform beach slopes, while the northern profile presented accentuated morphologies more frequently. This is the same for the center profile, which also presented the higher slopes.

Bahía de los Vientos beach (BV) (Fig. 3b) is a narrow pocket beach with a mean width of 40 m. It develops at the foot of a 4 m high active cliff. Since the end of 2008–2009, coastal defenses have been constructed. These defenses consist of a rip rap structure parallel to the coast at the base of the cliffs. The beach profile (Fig. 4d) presents great

Fig. 3 **a** CB beach (22 Oct 08). **b** BV beach and the post-wave storm scarp (21 Sep 07). **c** Collapsed rocks and cliff retreat after an intensive erosive period in BV (18 Mar 08). **d** A beach (30 Aug 06). **e** K beach and resort (07 Dec 07). **f** MB beach (30 Aug 06)

variability and it is affected by wave storms. In autumn of 2006 one of the most elevated topographic levels of the studied period was recorded. A storm registered at the end of June (Bértola et al. 2007) formed a 0.9 m high erosion scarp (Fig. 4d). It increased the foreshore slope from 4.8 to 8.1 % (Table 4) with no volume loss. The slope from the berm crest to the end of the profile was 27.3 %. During the winter of 2007, after an accumulative period (summer–autumn 2007), an intensive wave storm (Fig. 2) formed a very steep erosion scarp (1.35 m high), with a low volumetric loss (18.1 m^3) (Table 3; Fig. 3b). In summary, the erosive periods were recorded in winter, spring and summer with values from −15.4 to −703.1 m^3 (Table 3). The most erosive period was summer 2008. Collapsed rocks and cliff retreat with a strong decrease in the topographic level and beach slope were observed. These processes were associated to a wave storm event previous to the survey (Fig. 4d). Autumns and the summer 2007 were the accretion periods. The net sedimentary balance resulted negative with an erosive value of 114.4 m^3 (Table 3). No data of the wave gauge were available from May to September of 2009, but a significant wave storm occurred from the 20th to 25th of July causing an important storm surge. Tide and wave height was 3 and 5 m, respectively (Diario La Nueva Provincia 2009). This event caused important damages in the coast of the Necochea Municipality. Nevertheless, after a period of calm wave climate, BV did not recover. Beach slopes at BV are the steepest in the study area (Table 4). Their mean values are 8 % for total slope and 7.7 % for the foreshore slope. Since October 2008, beach slopes have increased given that the occasionally observed backshore disappeared under the rip rap, moving the cliff toe line toward the sea. At the end of 2009, almost a year after works on the rip rap ended, there was no migration of the beach environment as expected from the construction of this coastal defense.

Asilo beach (A) (Fig. 3d) is situated in the city of Necochea, 1,800 m southward of the South breakwater of the port. With a mean width of 280 m it constitutes the most extensive beach in the Necochea Municipality. Few morphological and volumetric changes were observed in A (Fig. 4e). These changes were mainly due to anthropic

Table 3 Beach volume (m^3)

Date	Beach volume				
	CB	BV	A	K	MB
28 Feb 06–26 May 06	26.1	82.28	213.71		49.15
26 May 06–05 Jul 06	−11.7	264.9	−1.1		−35
05 Jul 06–30 Aug 06	34	−327.7	−400		8.6
30 Aug 06–27 Nov 06	−12.3	−197.5	226		26.5
27 Nov 06–24 Apr 07	−25.7	128.6	333.6		56.8
24 Apr 07–03 Jul 07	30.3	146.4	−321.6		347.8
03 Jul 07–21 Sep 07	−28.4	−18.1			−163.5
21 Sep 07–07 Dec 07	−129.3	−15.4		10.4	−101.3
07 Dec 07–18 Mar 08	−90.2	−703.1		1077.3	−197.9
18 Mar 08–16 May 08	575.1	876.5		585.5	55.4
16 May 08–15 Jul 08	−483.1	11.3		−404.2	−140.1
15 Jul 08–22 Oct 08	19.5	−225.2		49	−89.7
22 Oct 08–28 Apr 09	−112.8	–		−56.6	−102.6
28 Apr 09–26 Jun 09	8.6	138.7		−90.5	110.2
26 Jun 09–16 Oct 09	22.5	−275.9		−154.4	−363.7
16 Oct 09–14 Dec 09	−64	−0.7		−402.4	
Total	−241.2	−114.8	50.6	614.2	−539.3

activities in the foredune and backshore since the profile does not present important variations after wave storms. The net sedimentary balance was slightly accumulative (50.6 m^3) (Table 3). The beach slopes are the lowest in the municipality with values around of 2.5 % (Table 4).

Kabryl beach (K) (Fig. 3e) is located in the Miguel Lillo Park and it develops at the foot of a 4 m high inactive cliff partially covered by forested dunes. The profile (Fig. 4f) is close to the public access of the beach resort Balneario Kabryl. The wave storms have minor morphological effects and cause small volumetric losses. However, a pronounced scarp was formed during the July 2009 storm in the dune toe. This event caused a significant deterioration of the resort infrastructure. The main morphological changes are induced by the equipping of the beaches for the summer recreational exploitation (anthropic actions). During the period spring–summer 2008 the layout of the access stairs was modified as well as the vegetation surrounding it. This action generated movements of sand causing a meaningful increase in the beach volume (1,077.3 m^3) (Table 3) and morphological changes in the dune toe and backshore (Fig. 3e). Although the rest of the period considered was erosive, the final sedimentary balance was accumulative (614.2 m^3) (Table 3). The beach slopes are medium with mean values of 3.8 % for total beach and 3 % for foreshore. The lowest values occurred in October 2009 (Table 4).

Médano Blanco beach (MB) (Fig. 3f) develops at the foot of a 6 m high cliff with sand ramps. The coastal road separates it from a vegetated dune field in Miguel Lillo Park. The wave storms cause minor morphological changes and low volumetric losses. Sediment migrations of different magnitudes were observed from the dune toe or sand ramp to the bar and trough during the winters (Fig. 4g). In the last period considered, during winter–spring, the lowest topographic level was recorded with an erosive value of 367.7 m^3. This event is associated to the wave storm and storm surge that occurred in July 2009 and the following storms (Fig. 2). Nonetheless, the absence of events during November and December did not allow the beach recovery. The accretion periods were registered during the year 2006 and in the winters, while the rest of the period was erosive. The final sedimentary balance was negative (−539.3 m^3) (Table 3). The slopes of MB beach are medium with mean values of 4 % for total beach and 3.3 % for foreshore (Table 4). The lowest values were measured after the erosive periods.

Discussion

Beaches west and east of the Quequén Grande River estuary differ notably in their grain size composition, width, slopes and sedimentary balances. The sedimentary balances analyzed evidence erosive processes through most of the year. Winter and spring are the most erosive periods, while autumn is the only season with accretion processes. Nonetheless, in several opportunities the accumulation-erosion cycles did not match in all beaches. This behavior was observed in other beaches of Buenos Aires province (Isla et al. 2001; Bértola et al. 2009). Anfuso and Gracia (2005) have observed erosive and accretion periods with no

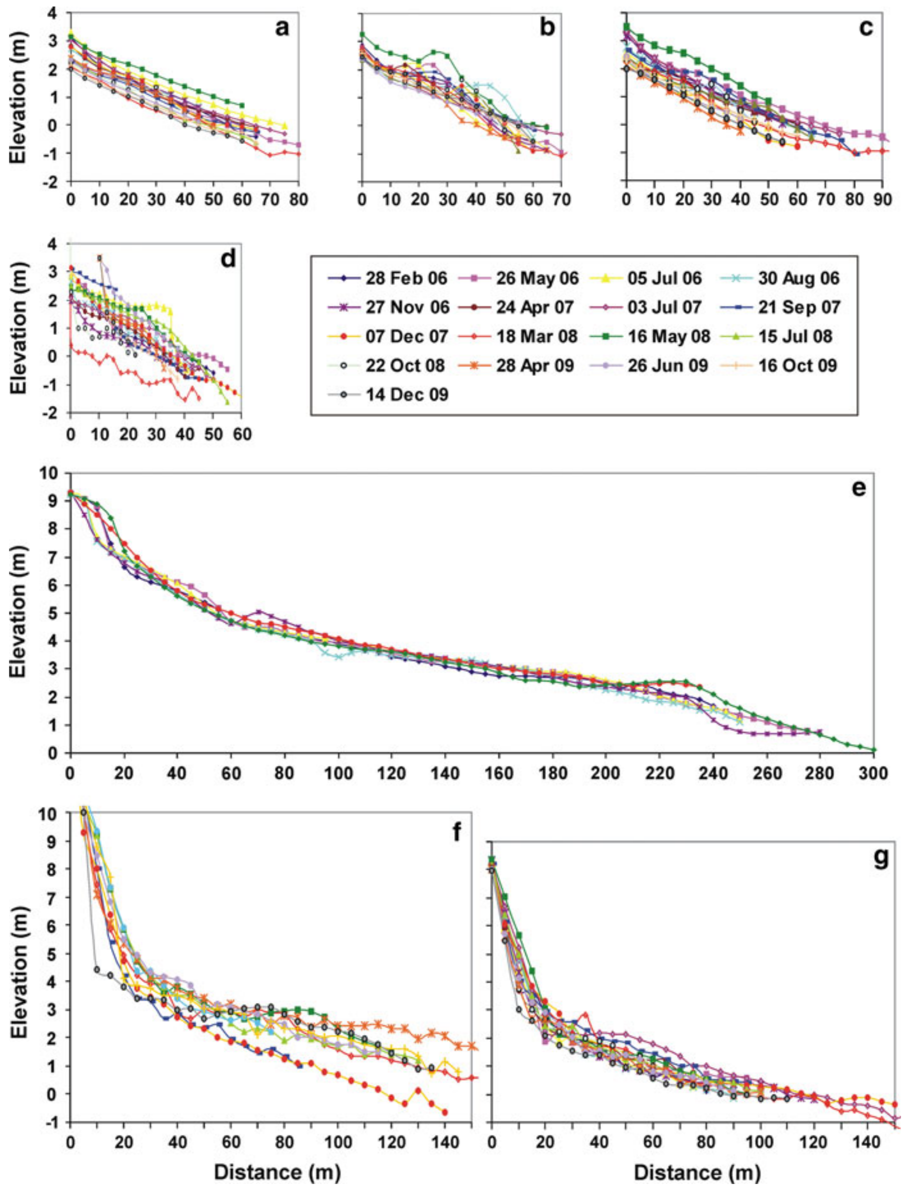


Fig. 4 Beach profiles. **a** CB South profile, **b** CB Central profile, **c** CB North profile, **d** BV profile, **e** A profile, **f** K profile and **g** MB profile

uniform trend in beaches at urbanized sectors of the Spanish coast associated to the interaction between weather conditions and natural or anthropogenic structures. In the study area, seasonal cycles and the configuration of the beach profile are influenced by wave storms, which reduce the transition or accretion periods to a few weeks or shorter, making them imperceptible between seasonal profiles. Episodic cycles linked to wave storms have also been observed, causing volumetric variations in typically accumulative seasons.

Beach morphology depends on two main factors: wave conditions and the exchange of sediment between the berm and the bar. Beach responses can be cyclic instead of summer–winter, constituting sequences of beach profiles with or without bar that depend on wave conditions during storms or during calm periods (Masselink and Hughes 2003). Some beaches can suffer important foreshore modifications and bar migration, berm and dune toe erosion, slope reduction and scarp formation (Lee et al. 1998; Benavente et al. 2002), overtopping or over washing (Regnauld et al. 2004). Likewise, other beaches may stay stable or present accumulation (Regnauld et al. 2004). Beach vulnerability to storms depends on the difference between storm frequency and beach recovery time, therefore storm effects can be accentuated if storm frequency exceeds the beach recovery period (Morton et al. 1995; Isla et al. 2001). A group of successive storms in a short period of time can have a considerable impact on coastal morphology producing consequences that exceed those of a single event (Ferreira 2005).

In the study area, wave storms did not necessarily produce loss of sand volume at the beach. The profile could

Table 4 Total and foreshore slopes (%)

Date	Beach slope									
	CB		BV		A		K		MB	
	T	F	T	F	T	F	T	F	T	F
28 Feb 06	5.5	4.6	6.9	5.4	2.6	2.2			5.1	4.9
26 May 06	4.5	4.8	5.9	4.8	2.5	2.2			3.9	2.8
5 Jul 06	5	5	7.7	8.1	2.6	2.5			4.9	3.9
30 Aug 06	4.6	4.3	7.3	6.4	2.6	2.2			4.6	3.7
27 Nov 06	5.3	4.9	5.2	3.3	2.4	2			3.1	2.3
24 Apr 07	4.1	4.3	5.8	5.5	2.6	0.9			4.9	4.1
3 Jul 07	4.6	4	5.8	5.8	2.9	2			2.2	2.3
21 Sep 07	4.4	4.7	8.6	9.6			4.9	4.1	4.3	3.3
07 Dec 07	5.1	5.1	7.6	6.4			4.4	3.2	3.1	2
18 Mar 08	3.7	3.4	4.2	4			3.1	2.4	3.7	3.5
16 May 08	5.1	4.8	6	6.5			4.3	2.9	4.1	3
15 Jul 08	5	4.8	7.5	8			3.4	2.7	4	3.3
22 Oct 08	4.9	4.3	10.7	10.7			4.8	4.8	5.4	4.2
28 Apr 09	5.4	5.4	11.2	11.2			2.9	2	3.1	3.2
26 Jun 09	4.8	4	11.1	11.1			4.2	3.3	5	4
16 Oct 09	4.7	4.4	9	9			2.7	2.5		
14 Dec 09	4.7	4.7	14.9	14.9			2.8	2.4	3.2	2.3
Mean	4.8	4.6	8	7.7	2.6	2	3.8	3	4	3.3

have been increasing its topographic level with the effect of the wave storm expressed in erosive features as a scarp, but not resulting in an erosive period. Consequently, the effect of the storms is not only observed through volume variations but also in the profile configuration. Retreats and advances of the dune toe or sand ramp were observed between surveys with the formation of erosion scarps. In most cases, after a period of calm waves the beaches began their recovery. Nevertheless, when beaches were affected by prolonged or successive wave storm conditions (sometimes extreme) alternated with calm periods, higher sand volumes were lost and the morphologic changes were more notorious because recovery between storms is insufficient. Likewise, after negative sedimentary balances, storm effects were more accentuated in morphology as in beach erosion and coastline retreat. Therefore, initial morphology of the beach profile would influence the response of the beach to a wave storm. The pre-storm profile morphology determines the volume of sediment needed to be transported during an event for the profile to reach an equilibrium state according to the prevailing wave conditions (Larson and Kraus 1994). Storms also produce sediment transport. Berm migration and the formation of a bar have been observed, with the reduction of the beach slope, evidencing offshore transport. Less frequently it has been noted that some beaches lost sand while others, toward the east, registered sediment accumulation. This process evidences longshore sediment transport. This behavior has been mainly observed between the south and north profile of CB.

In summary, the most affected beaches by wave storms are those of Quequén and to a lesser extent those of Necochea. These are comparatively less influenced by human structures and activities. Hill et al. (2004) studied urbanized and non-urbanized beaches response to wave storms and found that urbanized beaches do not recover to their pre-storm conditions as fast as the non-urbanized beaches, due to the lower sand storage of the profile. In the study area, the lower storage of sediments in Quequén beaches with respect to that of Necochea increases their vulnerability to storms and the time to beach recovery. Also, the volumes eroded or accumulated between periods are relatively larger in Quequén beaches. This variability could be related to the nearby coastal defenses, as observed by Anfuso et al. (2006) in the coast of Morocco. Lizárraga Arciniega et al. (2007) estimated that in Mexico the coastal structures and the rocky outcrops modified the wave incidence altering the littoral sediment transport and producing erosion and accretion zones. In the study area, A beach, situated toward the west of the port, did not present volumetric changes. K beach presented an increase in its sedimentary volume while in MB there was a decrease. CB and BV beaches are located to the east of the breakwaters and down drift, and present a rocky platform and active cliffs. These characteristics make them vulnerable to the changes in the availability in sediment supply.

The coastline retreat rates in the study area are similar or inferior to those of the eastern municipalities of Buenos Aires province. Pinamar has experienced an erosion rate from 1 to 2.3 m/year (Isla et al. 2001) while Villa Gesell has registered some stable sectors and others with erosion (Isla et al. 1998). Merlotto and Bértola (2009) have estimated a coastline retreat rate of 5.16 m/year over a 50-year period at Balneario Parque Mar Chiquita.

In Necochea, the coastline has remained stable or has advanced in response to different causes, all related to human activities. In Quequén, the coastline retreat is evidencing a significant erosive process, originated by multiple causes that are not consequence of a particular action in one transect. The stability of the coastline at Necochea allows estimating that the sediment supply is similar to that which formed the coastal environment. However, from 2006 to 2009 a negative sedimentary balance was verified at MB, although it was positive at K beach with a succession of negative balances. This would indicate an incipient erosion process and a decrease in the sedimentary supply. The advances registered to the west of the port obey human actions carried out to fix the foredune and the construction of beach resorts. These actions produced an advance of the beach environment toward the sea, favored by the sediment accretion caused by the breakwaters of Puerto Quequén. In the east of Miguel Lillo Park, the construction of a coastal road and the development of the community gated Barrio Cerrado Médanos, caused the advance of the dune toe line because of the leveling and fixation of the dunes. The small retreating sector detected in the area is attributed to the presence of a drain. Toward the west of the study area, the partial fixation of the dune fields by vegetation (Bértola and Merlotto 2010) has not affected the beaches since no changes in the coastline were observed.

At Quequén, in CB the coastline retreat was reduced in half between the periods 1967–1984 and 1984–2004, while for the same intervals it was doubled at BV. By 1984 the construction of the coastal road in the west of CB caused the retreat of the foredune. After that, the groins of CB stabilized the coastline in front of them and toward the west. Likewise, they would be the cause of the increase in the erosion rates eastward. Nevertheless, the construction of coastal defenses can led to negative consequences on the cliff structure due to inappropriate cuts of their slopes. The rip rap structures performed in BV caused these damages into the cliff profile.

The erosive process can also be related to the fixation of the dune fields by urbanization and forestation. The foundation of Necochea and Quequén cities and their posterior expansion was at the expense of the dune field that was removed, leveled and fixed. Since 1984 there has been an increase in forestation in the Miguel Lillo Park, which in 1967 occupied 50 % of the present area. The excessive fixation of the foredunes has altered the natural beach dynamics and caused sedimentary disequilibriums in other localities (Isla et al. 1998). The cities of Quequén and Necochea are settled on an area previously occupied by extensive live dune fields. Since predominant winds in the study area are from the N and NW during all year, while the strongest winds are from the SW (Merlotto and Piccolo 2009), the eolian continental sediment supply to the beaches would have descended, particularly for Quequén, due to the presence of the city and the park. Only recently has this change affected the beaches of Necochea. Quequén beaches are further affected by the decrease in the sedimentary supply by littoral drift.

Isla et al. (2009) determined that offshore of Necochea and Puerto Quequén there is abundant fine sand in the submerged beach, while in front of CB the rocky platform has no sand cover. It is considered that a lower sediment availability eastward caused by the obstruction of the breakwaters is an important cause for the beach erosion in Quequén. This is because the main source of sediments, the littoral drift, is interrupted. Similar effects were observed in CB beach as stated above. The construction of coastal defenses has had negative consequences in the longshore sediment transport in numerous regions of the world (Lorenzo et al. 2007; Martínez del Pozo and Anfuso 2008; Merlotto and Bértola 2009; Xue et al. 2009).

Finally, among the natural causes that can affect the coastline evolution, besides the wave storms, the geological composition and the sedimentary structures can improve or decrease the cliff vulnerability to erosion processes. For example, the rainwater runoff can increase gullies density and shortly trigger cliff collapse or slab slides, contributing to the coastline retreat.

Conclusions

The study of the medium-term coastal evolution has shown that the coastline at Necochea has remained stable or has advanced while in the short-term, the analysis has evidenced an incipient erosion process. On the other hand, at Quequén the retreat of the coastline and the negative sedimentary balances (medium and short-term) are clearly indicating an accentuated erosion process. Likewise, the different grain size composition of the beaches evidences differences in the sediment supply to both sides of the harbor. The main factors that influence the coastal evolution are anthropogenic: dune field fixation by urbanization and forestation, and the breakwaters of Quequén Port. The infrastructure expansion has also caused erosion processes in some sectors. Regarding the natural factors, the erosion generated by wave storms is significant. Due to the volumetric and sedimentary characteristics of Quequén beaches, they are more vulnerable to wave storms than Necochea beaches. The magnitude of the consequences of the wave storms in the beaches also depends on the degree of human intervention in the area, since they restrict the response capability of the beaches. The recovery period can be delayed for several months under prolonged or successive storm conditions. Given the social and economic importance of the studied coastal environment, this study is an important contribution to the understanding of the evolution and behavior of the area. The results evidence the necessity to develop an integrated coastal management programme that considers, among others, the spatial and temporal variations of the environment.

Acknowledgments Authors would like to thank the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), since the study is part of the first author Doctoral thesis, developed through a postgraduate scholarship from this institution. Also, thank the Consorcio de Gestión de Puerto Quequén and the Municipalidad de Necochea (M. Sarasíbar and G. Molina) for the data provided.

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