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Recent Coastal Geomorphological Evolution in the Negro River's Mouth (41°S), Argentinean Patagonia

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ABSTRACT

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This paper analyzes the geomorphological evolution of the Negro River's mouth to understand how aerodynamic and hydrodynamic states of the Atlantic coast have developed to this date. Accordingly, the morphometry of the beach and the historical river flow record were studied. The results indicate a dichotomous state for this coast. The SW area is characterized by cliffs with an average recession rate of 0.69 m/y during the 1959–2011 period, whereas the NE area is characterized by beaches in stable and accretion states. In the latter zone, a relatively fast coastal accretion was corroborated with the advance of a berm of up to 170 m between 1986 and 2014; furthermore, the beach extension grew to 760 m during 1986–2004. Since 1936, a completely new phenomenon was observed at the Negro River's mouth: the displacement and accretion of intertidal banks toward the coast provoked the closure of the channels of fluvial discharge and tidal currents. This activity at the Negro River's mouth could be due to the reduction of river discharge during the 20th century, which increased the preponderance of littoral current over the river discharge.

ADDITIONAL INDEX WORDS: *Coastal processes, geomorphology, beach geodynamic, landscape evolution.*

INTRODUCTION

The global climate change associated with an absolute sea level rise on the order of 3.3 ± 0.4 mm/y has generated alarm in the world, calling attention to the research community (Ablain *et al*., 2009). However, the sea level fluctuations and the advance/retreat of coasts also depend on local conditions, such as tectonic, isostatic, and sedimentary processes precluding global generalizations (Davidson-Arnott, 2009). In fact, the sedimentary balance of the coastal environment and its consequent geomorphological expression (*e.g*., cliff, dissipative, or reflective beach, dune) are forced by geology, physical properties of the ocean and atmosphere, relative sea level trend, availability of sediments, and anthropogenic effect (Masselink, Hughes, and Knight, 2011). In particular, human impact is increasing worldwide because of population growth and the expansion of urban areas; therefore, it is increasingly fundamental to take this into account in coast morphodynamic analysis (Beer, 2009).

Geomorphological studies were carried out within the study area during the 1980s (Del Río, Colado, and Gaido, 1991), a sedimentary balance was performed by Colado *et al*. (1986) for the November 1985 to October 1986 period, and a beach morphodynamic analysis was conducted by Isla and Bertola (2003). The aim of this contribution is to analyze the geomorphological evolution to this date, considering sedimentary balance at an interdecadal scale and anthropogenic impact in the area. In this perspective, because of the current increasing population in the region, this contribution is important for geoclimatic hazard analyses and land use planning.

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Physical Features of the Study Area

The mouth of the Negro River is located in the NW Argentinean Patagonia, comprising 12.5 km of the Atlantic coastline (Figure 1). The riverbed forms the administrative boundary between the Buenos Aires and Río Negro provinces. The area is poorly populated, with the two main population centers being the villages of Balneario El Cóndor in Río Negro and 7 de Marzo in Buenos Aires, with populations of 746 and 40, respectively (Figure 1; INDEC, 2010). However, the population of Río Negro increases greatly over the summer months because of tourism, with inhabitants rising to more than 7000 in number (Del Río *et al*., 2004).

A semiarid and cold climate (BSk type by Köppen, 1936) predominates, with a mean annual temperature of 13.4°C and a mean annual precipitation of 310.3 mm (DPA, 2011). The dominant wind direction is between NW and NNE, and the second most frequent wind direction is between WSW and SSW (DPA, 2011); because of its greater speed, the latter is more effective for sand transportation (Cortizo and Isla, 2012).

The Negro River starts from the confluence of the Limay and Neuquén rivers, both of which rise in the Andes. This allochthonous and influent river is 635 km long and has a seasonal flow regime, with the lowest level during autumn. Its discharge is the greatest of Patagonia with a mean streamflow of 834.32 m^3/s, measured during the period 1927–2012. This river is an essential resource for the region because the economy of Patagonia is mainly based on agriculture, industry, and hydropower generation.

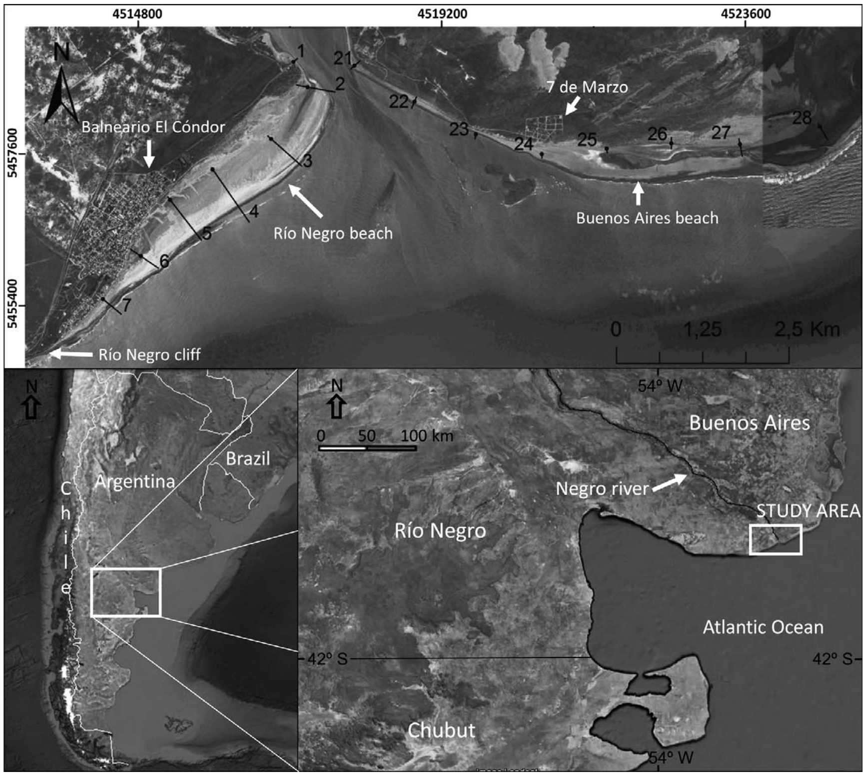

Figure 1. Location of the study area, the profiles studied, the Balneario El Cóndor and 7 de Marzo villages, the Río Negro cliff, and the Río Negro and Buenos Aires beaches.

Concerning the coastal geomorphology, the relative local sea-level rise is 0.1–2 mm/y (Kokot and Codignotto, 2003), lower than the current absolute sea-level rise, without considering local tectonics (Ablain *et al*., 2009). In this area, the mean tide range is 3.35 m high (mesotidal), although it may reach up to 4.15 m during equinoctial syzygy events. The cycle tide is semidiurnal, and tide currents reach speeds of 3.7–9.3 km/h (Del Río, Colado, and Gaido, 1991). The tidal wave is transferred upstream, with the Negro River losing energy until it becomes null nearly 70 km from the mouth (D'Onofrio *et al*., 2010).

The yearly average swell height was 0.67 m (maximum height 1.28 m), with a period ranging from 5 to 17 seconds for the year 1986 (Lanfredini, 1986). The dominant origin of the swell is from the SW quadrant, causing a littoral drift to the NE of 900,000 m^3/y (Lanfredini, 1986). The source of the sediments, which are transported without difficulty to the river mouth where they are temporarily detained by river discharge, is from the erosion of the Río Negro cliff (Del Río, Colado, and Gaido, 1991). During the rising tide, the transported sediments reach the Buenos Aires beach (Figure 1).

Geological Framework

All of the rocks that outcrop in the area belong to the Colorado sedimentary basin, formed in the context of a passive tectonic margin. The oldest rocks appertain to the Middle Member of the Río Negro Formation (Miocene) composed by a succession of horizontal sandstones interlaid with green shale banks (Andreis, 1965; Zavala and Freije, 2005). This unit emerges at the base of the Río Negro coastal cliff. The Superior Member (Pliocene) overlaps the previous one through an abrupt contact; it is composed of an alternation of gray-green sandstones with red claystones that show whitish tuff levels and paleosoils with mega-mammal remains (Alberdi, Bonadonna, and Ortiz, 1997; Zavala and Freije, 2005).

At the top of the sequence on the cliff and in the upper valley of the Negro River, the Tehuelche Formation of the Late Pleistocene age (Sepúlveda, 1983) appears. In this sector, the formation is more than 24,500 years BP, has a maximum of 2 m in thickness, and overlays the Río Negro Formation by erosional contact. This unit, associated with a fluvial environment, is composed by conglomerates of dark volcanic well-rounded clasts cemented by calcium carbonate in a sandy matrix (Schillizzi, Luna, and Falco, 2009). This sandy material might have originated from the erosion of the upper levels of the Río Negro Formation (Schillizzi, Luna, and Falco, 2009).

After the Last Glacial Maximum (20,000 years BP) begins the last transgression that peaks at the coast of Argentina between 6500 and 4000 years BP (Codignotto, Kokot, and Marcomini, 1992). During this transgressive period, the San Antonio Formation (Angulo *et al*., 1978) was deposited, forming a marine construction plain of unconsolidated material, such as coquinas, sandy gravels, and sands with shells of mollusks. It has a basal contact with the Río Negro Formation by erosional

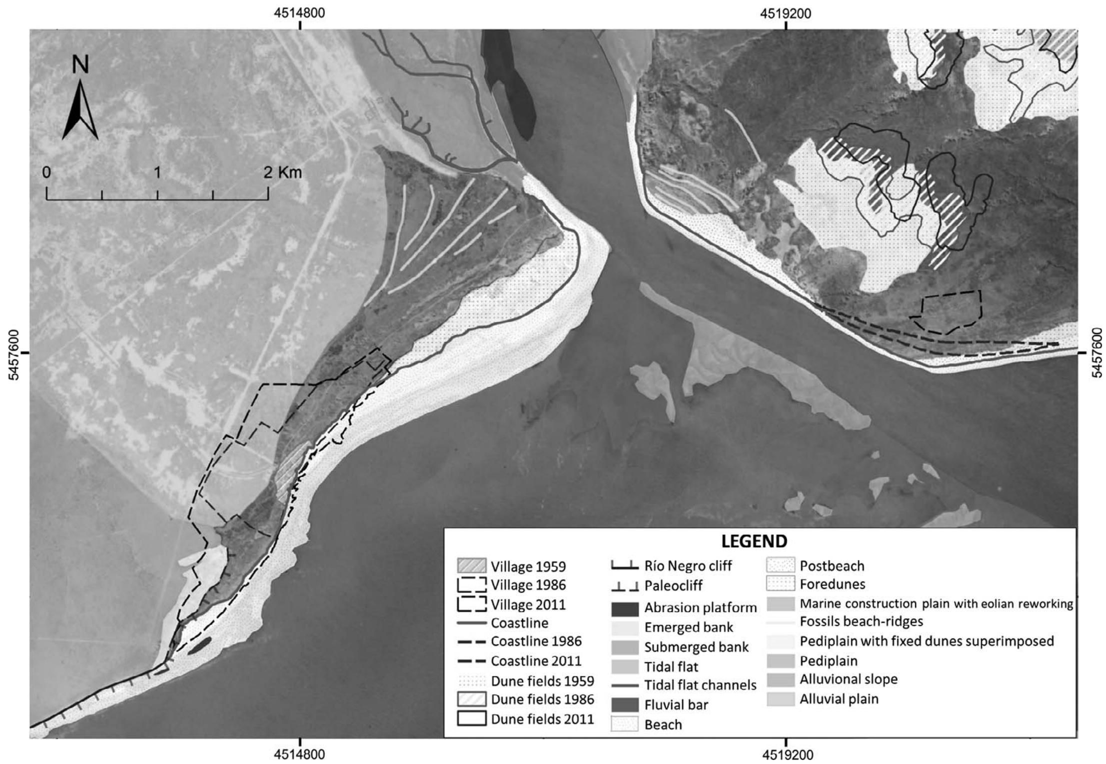

Figure 2. Geomorphological map showing the evolution in time of the studied area.

unconformity and outcrops on both sides of the Negro River's mouth, with more development on the left bank.

Following the maximum Holocene transgression, a regression began that lasted until 250 years BP (Kokot and Codignotto, 2003), which partially reworked the San Antonio Formation and formed beach ridges as a result of the advancing shoreline and dune fields of the continentalization. During this period, the environment was dominated by well-sorted eolian deposits of medium-fine sands and marine sand and gravel deposits with bioclasts of marine mollusks.

Local Geomorphology

From a geomorphological point of view, the study area could be divided into three main kinds of environments with different characteristics, backgrounds, and ages: the pediplain, the alluvial plain, and the marine construction plain with eolian reworking (Figure 2).

The pediplain is the highest (30 m above sea level) and oldest set of landforms. This semiflat surface was developed over the Río Negro Formation, and its detrital cover is about 2 m thick (Tehuelche Formation). The border with the marine environment is represented by active or inactive cliffs (30 m high), whereas the margin with the alluvial plain of the Negro River has an alluvial slope with a gentle inclination (3.83°) to the right bank of the river valley.

The alluvial plain of the Negro River is 10 km wide, limited by its narrow valley. This plain is located on the right bank of the river. The origin of this river seems to be Late Pleistocene, considering fluvial clasts are absent on a small marine layer close to the river mouth, dated at 125 ka (Zavala and Freije, 2005).

The last geomorphological group is the marine construction plain with eolian reworking that was generated from coastal processes during the last transgression. The marine construction plain is formed by the San Antonio Formation and other younger sediments, which are reworked products of the former: fossil beach ridges since the last marine regression (6500–4000 years BP), current beaches, foredunes, and active fixed dune fields.

METHODS

This article analyzes geomorphological processes that have occurred at the Negro River's mouth since 1959 and attempts to differentiate natural from anthropogenic geomorphological changes. In this regard, to compare landforms over time, the methodology was based on the interpretation of images of diverse remote sensors: aerial photographs from the Argentinean Geological and Mining Survey from 1959 and 30 December 1986, and digital terrain models and satellite images from 1999, 19 September 2004, 22 October 2011, and 10 August 2013, which were downloaded using the Google Earth software and from the Global Land Cover Facility (2013) website. The management and analysis of the plots was carried out with Quantum GIS software; the UTM WGS84 coordinate system was used.

In October 2014, seven topographic profiles were surveyed using a differential global positioning system (GPS). The

Table 1. *Backshore width from 1986 and 2014, displacement of berm between 1986 and 2014, and elongation of profiles for the 1986–2004 period. Measures of profile 1 width were not taken because the berm was not recognized*.

Profile	Width 1986	Width 2014	Berm Movement	Elongation 1986–2004
2	262.5	197.82	10.32	Negligible
3	255	674.11	165.77	344.93
4	400	598.08	115.08	157.3
5	427	596.71	169.71	65.51
6	235	337.17	102.17	70
7	70	80	10	Negligible
25	—	—	—	647.97
26	—	—	—	762.97
27	—	—	—	486.44
28	—	—	—	165.82

sections were done perpendicular to the Río Negro beach, covering the area between the Negro River's mouth and the Río Negro cliff (area between sections 1 and 7, Figure 1). The profiles were performed during a calm weather period and ahead of the summer storms that usually occur between December and February. These profiles were done following previous transects carried out by Colado *et al*. (1986), starting at the same point and in the same direction. The profiles surveyed by Colado *et al*. (1986), were measured at low tide and every 2 months during the November 1985 to October 1986 period (six times).

To observe the temporal morphometric variations of the beach for 28 years, the backshore profiles introduced in this paper and those profiles made by Colado *et al*. (1986) were compared. However, this comparison does not unequivocally indicate the sedimentary balance of the backshore. The migration of the beach limit is estimated in this case by the location of the foredune, which could also be modified by anthropogenic degradation or changes in climatic parameters. For this reason, the estimated sedimentary balance was established with the movement of berms toward the mainland or sea and considering the initial location of the foredune in the 1985–1986 profiles.

At the same time, annual average discharge series for the Negro River measured at the Primera Angostura station (located 105 km from the mouth) during the 1927–2012 period was analyzed. The data were registered by Subsecretaría de Recursos Hídricos (SSRH, 2013), and each year starts in April when drought occurs in the hydrological year. The tests of Mann and Kendall (Hirsch, Snack, and Smith, 1982; Westmacott and Burn, 1997) and Mann and Kendall with corrections for autocorrelated series, prewhitening (Yue, Pilon, and Cavadias, 2002) and variance (Hamed and Rao, 1998), were used to establish the river flow trend. An $\alpha = 0.05$ was considered in all tests.

RESULTS

The main outcomes of this study are subdivided into three approaches: the geomorphological evolution of the Patagonian coast section, types and morphometry of beaches found in this coast, and the analysis of anthropogenic impact.

Geomorphological Evolution

Based on the data generated in the Quantum GIS, temporal changes in the landforms were studied. Additionally, a geomorphological map showing evolution through time was drawn at a scale of 1:50,000 with images from 1959, 1986, and 2011, where the mappable landforms were superimposed to detect spatial variations (Figure 2).

Río Negro Cliff

For this landform, an average recession rate of 0.69 m/y was measured for the 1959–2011 period, a slightly different value from the 1.14 m/y calculated by Del Río *et al*. (2004) for a similar period. The retraction is manifested by debrisfall or rockfall (Schillizzi, Gelos, and Spagnuolo, 2004).

Río Negro Beach

A sedimentary stability was observed for the sectors located between profile 6 and the cliff and between profiles 1 and 3 (Figure 1). In contrast, in the area located between profiles 3 and 6, an increase in the extension of the profiles, from 65.51 to 344 m, was observed for the period 1986–2004 (Figure 1 and Table 1). These measurements were obtained comparing the points farthest from the continent in the 1986 profiles, with the farthest points from the continent located on the same transects in a satellite image taken in 2004 during low tide.

Mouth

A counterclockwise movement of the main channel was observed between 1959 and 2011 (Figures 3a–e). This change coincides with that observed by Del Río, Colado, and Gaido (1991) during the 1936–1986 period and with the retreat that occurred between 1959 and 2011 of the microcliff, with a height of 2–3 m, developed on the San Antonio Formation between profiles 23 and 25 (see the section below). Another modification was the accretion of the La Hoya bank with the Buenos Aires coast during the 1999–2004 period (Figures 3c and d), which led to the disappearance of the eastern secondary channel and was confirmed by the elongation expressed by the beach profiles in the amalgamation area (see the section below). Finally, a displacement and a subsequent coupling of at least part of the Miguel bank with the Buenos Aires coast was inferred, producing the obstruction of the Main channel and the formation of a new one. Indeed, the analysis of the image of 2011 (Figure 3e) shows that the Miguel bank (the bank that separated the secondary channel from the main channel between 1959 and 2011) is divided into two, whereas the 2013 image (Figure 3f) demonstrates that the eastern fragment (product of the division of the bank) adheres to the Buenos Aires coast, interrupting the Main channel and forming a new one.

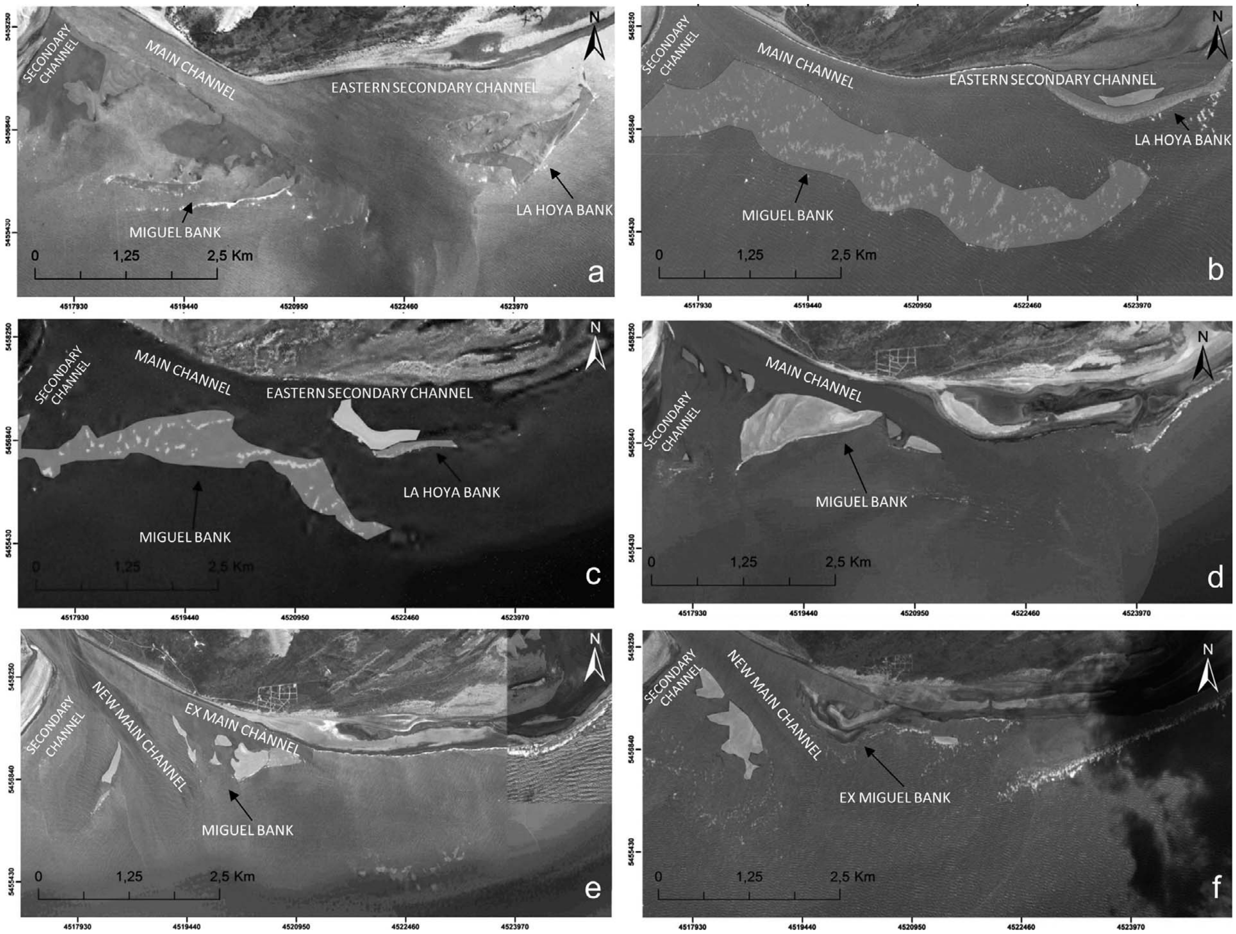

Figure 3. Graphic representations of the mouth over time: (a) 1959, (b) 1986, (c) 1999, (d) 2004, (e) 2011, and (f) 2013. Sectors of the submerged banks represented in dark color and sectors of the emerged banks represented in light color at the time of capture.

Buenos Aires Beach

This landform was studied using the profiles of Colado *et al*. (1986); these were used for spatial reference and to measure lengthening profiles. Between sections 21 and 23 a sedimentary stability was deduced (Figure 1). Between profiles 23 and 25 an erosive sedimentary state was recognized that was measured by a microcliff mean retreat rate of 4.05 m/y for the 1959–2011 period (Figures 1 and 2). Finally, an accretionary phenomenon was identified between transects 25 and 28 as a result of the amalgamation of the La Hoya bank to the mainland. It is manifested by increases in the lengths of the profiles from 165.82 to 762.97 m during the 1986–2004 period (Figure 1 and Table 1).

Some sectors of the backshore of the Buenos Aires beach were naturally vegetated over time, indicating stabilization. The areas where this phenomenon was observed were called postbeaches, and it was decided to draw the coastline in front of them because, although they initially belonged to the beach environment, over time they were continentalized (Figure 2).

Dune Fields

For the dune fields, an advance rate of 7.03 m/y was measured in the N60°E direction, with a total area reduction of as much 55.75% from vegetation (Figure 2). These measurements were calculated for the 1959–2011 period and are similar to those obtained by Cortizo and Isla (2012).

Types and Morphometry of Beaches

In general, coasts are mainly divided into cliffs associated with a negative long-term balance and beaches with a positive or neutral long-term balance as a function of its sedimentary state and geomorphology. Nevertheless, aero-hydrodynamic changes and continuous mutations of such landforms prevent the use of these general relationships in the short term (Davidson-Arnott, 2009). At the same time, beaches could be classified as reflective, intermediate, or dissipative, depending on tidal range and their υ parameter (dimensionless fall velocity), a coefficient that considers the velocity of mean grain decantation, wave altitude, and wave period (Wright and Short, 1984).

The presence of reflective beaches characterizes the study area showing a narrow surf zone, coarse grain deposits, sudden

Table 2. *Morphometric parameters width (m) and slope (°). The distance between the topographic profiles (m) is also indicated.*

Profile	Total Beach		Backshore		Foreshore
	Distance Successively Profile	Slope	Slope	Width	Slope
1	420.03	6.08	—	—	—
2	921.56	—	−0.14	197.82	2.24
3	955.7	—	0	674.11	1.66
4	758.24	—	0	598.08	2.56
5	922.01	—	−0.05	596.71	1.42
6	829.84	—	0.02	337.17	1.11
7	—	—	−0.17	80	1.71

dissipation of wave energy, and a steep slope (Martínez, 2010). Two main types of beach are particularly identified in the Río Negro beach: (1) with direct river influence and (2) with indirect fluvial influence. The first type (1) is located from profile 1 toward the SSE up to profile 2 (Figure 1). It is characterized by a narrow backshore, slopes of about 6°, and an absence of berm (Table 2 and Figure 4). The second type (2) is located from profile 2 toward the SW up to the Río Negro cliff (Figure 1); it has a wide backshore that gradually decreases toward the SW from 674 to 80 m, the presence of berm and usual intertidal channels, a slope in the backshore from zero to slightly negative, and a slope in the foreshore from 1.11° to 2.56° (Table 2 and Figure 4).

The comparative morphometric analysis shows evidence that all berm migrations were positive, moving toward the sea and not backward (to the mainland) during the 1986–2014 period (Table 1). In those cases, where beach migration is on the order of 10 m, the influence of berm seasonal variation could be postulated; however, when beach migration is approximately 100 m, it is more likely that this movement indicates an accretionary phenomenon.

Anthropogenic Impact

Human influence in a certain area not only changes the landscape but can also alter the dynamics and relationships between several of its natural components. To study anthropogenic impact, the territory was divided into four sectors, and the research focused on effects that could alter the coastal dynamics, setting aside purely landscape alterations.

Río Negro Cliff

On this landform, erosion is a natural and typical phenomenon; however, the construction of the Picoto access to the beach slightly accelerates the local erosion process. In fact, according to Camino *et al*. (2007), this infrastructure accelerates the decline of the coastline, stimulating badland formation because of an increase in surface runoff (a consequence of an artificially steeper slope), lower sinuosity of the ramp, and the obliteration of native vegetation cover. Another factor of uncertain impact that could accelerate the decline of the coastline is the effect of vibrations from vehicular traffic on Provincial Route 1, which is a minimum distance of 27 m from the cliff.

Río Negro Beach

Human influence in this area is related to an increase in susceptibility to erosion during storms because of (1) afforestation of foredunes that reduces the natural sand exchange between them and the beach, (2) buildings on the backshore that increase erosion by the reflection of the waves, and (3) movement of vehicles on the beach environment that alters the natural morphology.

Despite the modifications, the coastal aero-hydrodynamics did not show noticeable changes.

Mouth

A significant decrease in the sediment and liquid river discharge was verified during the last century, in part because of anthropogenic disturbances upstream; these changes may have affected the study area. The decrease in sediment discharge was caused by the construction of six dams on its only two tributaries since 1972; this change evidently modified the relationship between the sediment of fluvial origin and from littoral drift.

The linear regression of the annual hydrograph shows a significant negative trend of 2.91 m^3/s per year (Figure 5). The *p* values of the Mann and Kendall test and the Mann and Kendall test with corrections for variance and prewhitening are 0.007, 0.025, and 0.004, respectively. The decline in liquid discharge was due to natural and anthropogenic causes, which were (1) lower precipitation from climate variability in the basin of the Limay river (Masiokas *et al*., 2008), (2) an increase in water evaporation from the rivers by artificial dams, which increased the residence time of water on the continent, and (3) the artificial afforestation of the Negro River valley in the 20th century, which increased water loss through evapotranspiration of irrigated crops and the potential aquifer recharge by overwatering.

DISCUSSION

Given the climate and population scenarios of the 21st century, studies that seek to understand the current aerodynamic and hydrodynamic states of our coasts are fundamental. Understanding the evolution of landforms is essential to detect anthropogenic influences and avoid mistakes in land use planning; therefore, the mapping and description of present landforms, obviating their relative ages, is not enough. The importance of landforms is remarkable, because previous studies on coastal dynamics in this fluctuating area have been scarce, and the ones that were carried out 10 years ago have not been updated. Other studies have instead focused on regional analysis, sidestepping local landscape features.

Early geomorphological studies (Del Río *et al*., 2005) ignored the activity of the landforms of the Río Negro beach, the intertidal banks, the dune fields, and the Buenos Aires beach (including the microcliff). Although the Negro River's mouth dynamics have been analyzed from 1936 (oldest existing map of

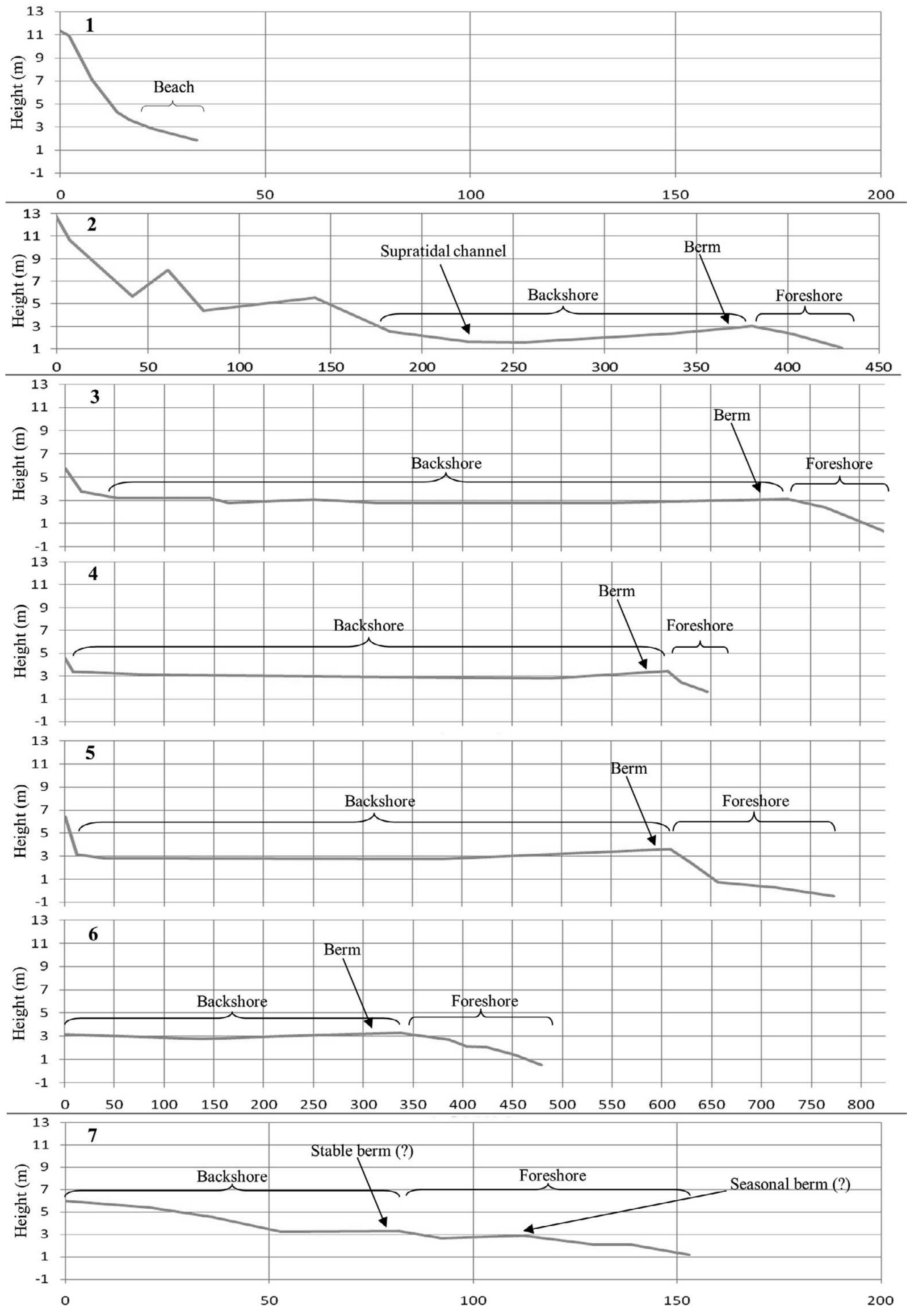

Figure 4. Topographic profiles. The *x* axis is the horizontal distance (m). Profiles 1 and 7 show a vertical exaggeration of 2.8, profile 2 of 5.2, and profiles 3, 4, 5, and 6 of 11.1.

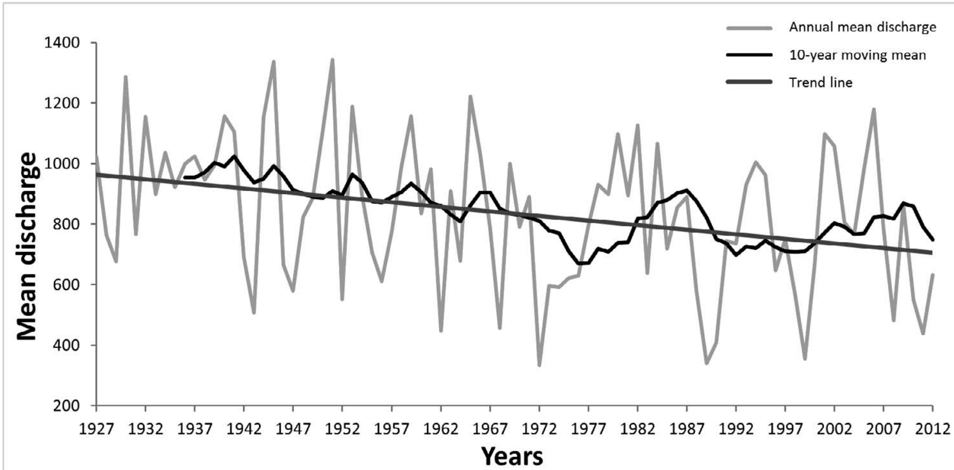

Figure 5. Annual average streamflow series of the Negro River.

the study area) to 1986 by Del Río *et al*. (1991), they never documented the amalgamation of banks to the coast (La Hoya and Miguel) and the resulting closures of the channels (main and eastern secondary), ignoring these kinds of phenomena. This research instead recognizes that these amalgamations and consequent closures of channels are more likely associated with the significant negative tendency of the Negro River streamflow. The hypothesis is that the decrease of river discharge should favor prevalence of the littoral current on the river discharge and tidal currents, which has led to a greater movement of banks in the ENE direction. With the same reasoning, the counterclockwise movement of the main channel could be caused because it is energetically easier for the river discharge to erode the coastline by reducing the angle to the current littoral, rather than cutting the Miguel bank perpendicularly to the said force acting mode. The findings herein remove the uncertainty noted by the study of Del Río *et al*. (1991) about the influence of hydraulic regulation on the dynamics of intertidal banks, as dam construction upstream collaborates in the decrease of river discharge.

Concerning coastal sediment dynamics, Del Río *et al*. (2004) measured retreat velocities of the cliff for a similar period to this study; nonetheless, monitoring of the beach system was carried out only in 1986 (Colado *et al*., 1986). Thus, these results are not completely certain because the values are conditioned by interannual variability. Furthermore, the analysis in this paper allows the understanding of coastal sediment balance in different beach sectors, by contrasting methodologies, such as image interpretation and comparative morphometric analysis. The increment of values in the beach profiles and the berms sliding seaward are unequivocal proof of the accretionary state of the beach between profiles 3 and 6 since 1986; however, the interpretation of images from 1959 and 1986 hint that the accretionary phenomenon already existed during that period.

In the regional coast morphodynamic study performed by Isla and Bertola (2003) in the north Patagonia beaches, only an isolated transverse profile was measured, disregarding local longitudinal changes. Instead, in this research, several profiles were made along the beaches of the Río Negro province that let us distinguish two types of beaches. Furthermore, a widening toward the NE was recognized as type (1), caused by river discharge that behaves like a hydrodynamic dam with a SSE direction that slows the littoral NE current, causing an increase of deposition in the proximity of the river mouth, where the transport of sediments is more difficult.

CONCLUSIONS

Three geomorphological groups were identified, all of late Pleistocene origin: the pediplain of fluvial origin and older relative age, the alluvial plain formed from the Negro River with a middle relative age, and the marine construction plain formed in the last marine transgression.

Within these groups, the landforms that had activity in the last 50 years were the cliff, the Río Negro beach, the intertidal banks, the dune fields and the Buenos Aires beach (including the microcliff).

From a geomorphological and current sediment balance perspective, the coast can be divided into two main areas: cliff with a mean retreat rate of 0.69 m/y and Río Negro-Buenos Aires beaches in different states: stable, accretionary, and exceptionally erosive.

Exogenous processes are not anthropogenically altered except at the mouth of the river, where the reduction of river flow on the littoral current appears to have caused the displacement of banks to the ENE and the closures of the channels of river discharge and tidal currents. More studies are being conducted to verify this hypothesis and more comprehensively understand the complex behavior of the mouth.

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