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RELATIONSHIPS BETWEEN THE SAND CYCLE AND THE BEHAVIOUR OF SMALL RIVER MOUTHS: A NEGLECTED PROCESS

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Abstract

This article aims to advance in the knowledge of the relationships between the sand cycle and the behaviour of small river mouths (outlets) flowing into sandy beaches in the Río de la Plata estuary, Uruguay. The bars of these watercourses respond quickly with processes of erosion and/or migration of the channel when the "sand cycle" (coastal sedimentary balance) undergoes modifications, due to i) the effect of the fixation of dunes (sediments) by afforestation with exotic species and ii) the construction of infrastructure. Two watercourses were analysed: the Pando River and the Carrasco Creek that both have received different impacts and suffered modifications, not only in the sediment flow but also in their hydrological regime. A multitemporal analysis was based on a series of aerial photos and cartography since 1928, a background review, and the support of documents and chronicles. The data obtained were analysed statistically. Results evidence a significant loss of beach surface at the Pando River mouth, and an increase at the Carrasco Creek mouth, since the channelling of a wetland located upstream, allowing the entrance of sediments from the basin upstream of the wetland. Relevant outcomes are: i) the description and analysis of the relationships established between dune systems and the outlets of the watercourses, an aspect that has not received due attention in the scientific literature, in which the dissociation between the analysis of wind and fluvial dynamics is usual, and ii) the sedimentary balance was of both systems: erosion and accretion at the Pando and the Carrasco outlets respectively. The reconstruction of the dunes could likely prevent the escape of sand and reduce the erosion. The knowledge about human intervention and natural processes governing the interactions between sandy beaches, dunes and outlets is a crucial input to coastal management and adaptation to sea-level rise and storm surges.

Keywords: Sand cycle. Sedimentary balance. Aeolian transport. Outlets-beach interaction. Human intervention. Río de la Plata estuary.

1. Introduction

Most of the population of the planet is concentrated in the coastal areas (Woodroffe, 2002; Small and Cohen, 2004), where they reside and develop activities such as agriculture, fishery, industry, tourism, mining and ports, within the framework of "development policies" that conceive the environment as an unlimited source of resources (Jonge et al., 2002; Nicholls et al., 2008; Martinez et al., 2017). This interpretation has led to the reaching of such a point of transformation, that it becomes difficult to avoid the final loss of environmental services of the coastal ecosystems

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(Luisetti et al., 2014; Carro et al., 2018; Martins et al., 2018). In turn, many of these investments or infrastructures have already lost their value or functionality, since integrated management of resources has not been carried out, suggesting that current development concepts are not sustainable, neither ecologically nor economically. In recent decades, the most significant alteration of coastal areas has occurred around the world, and as a result, large parts of coastal ecosystems are already under intense and increasing pressure, independently of climate-related changes (Turner et al., 1996; Klemas, 2011). When the climate-induced change is added to the above, very complex interrelations and feedbacks are generated between humans, the environment, the effects of the impacts produced and climate change (Luisetti et al., 2014; Chang et al., 2018).

The problem is increasingly complex, demanding a new conception of human interaction with an especially fragile environment (Martínez et al., 2013; Silva et al., 2014), as the coastal areas are the transition between continental and marine ecosystems. At the same time, it is difficult to interpret the impact of each activity in the narrow sandy strip of beaches (Burningham and French, 2017), and even less the responsibility of each human intervention in the observed processes, the effects of which can be manifested long after it occurs and be masked by other ones (Gutiérrez, 2016). Besides, the understanding of these alterations is complicated by other natural long-term trend processes (e.g. El Niño Southern Oscillation - ENSO, Atlantic Multidecadal Oscillation – AMO, North Atlantic Oscillation - NAO), whose dynamics are still little known, including the effects of changes in the wave climate or sea-level rise (SLR) (Gutiérrez et al., 2015; 2016; Verocai et al., 2015).

The landscapes of beaches with dunes are geomorphological response systems susceptible to environmental changes (Hansom, 2001). The response sensitivity of the relief forms can be defined as the ability of the landscape to undergo a recognisable shift in response to changes in the external control variables (Hanley et al., 2014). The nature of the reaction may vary depending on the intensity and direction of the change, the complexity of the system and the relaxation time required to reach a new equilibrium (Chorley and Kennedy, 1971). Sandy coasts are representative of a response system that adjusts rapidly in a labile form to changing environmental conditions (Hansom, 2001).

In the literature there are numerous works that analyse the sedimentary balance in beaches (Clayton, 1980; Inman and Masters, 1991; Pasternack and Brush, 1998; Willis et al., 2002; Vinther et al., 2004), or address the study of the dynamics of coastal dune systems (De Lillis et al., 2004), or study the evolution of estuaries and their exchanges of sediments (Carter and Bartlett, 1990; FitzGerald et al., 2000; Gelfenbaum et al., 2001). Although in some cases the existence of degraded dune systems is mentioned in these sites, the exchanges of sediments between dunes, outlets, and nearby beaches are not analysed. The review articles (e.g. Stephenson and Brander, 2003, 2004; French and Burningham, 2011), also do not mention works that relate to these exchanges. Quantifying the contributions and outputs of coastal sediments allows having an idea of the importance of individual sediment sources and sinks that affect the stability of beaches and, in turn, provide useful answers for agencies and policymakers that manage the coastal environment (Limber et al., 2008).

This work aims to advance in the study and knowledge of the sandy coasts of Uruguay, from the analysis of small river estuaries mouths (hereafter mouths or outlets), because these are particularly dynamic environments. To achieve this goal sedimentary balance estimates are being made which relate the different sources of sediments and their contribution to the equilibrium/disequilibrium of the beach sectors near the inlets.

In addition, an attempt is being made to understand the causal relationships that determine the observed changes and, as far as possible, to establish relationships between natural and human forcings in fluctuations of the coastline. This study would help to follow and anticipate trends associated with environmental change and its climatic causes and establish some adaptation measures. At the same time, it is intended to contribute to the dimensioning of the sand cycle component, due to the contribution of the active dune systems from the analysis of drainage channel mouths with and without active dunes in their original state.

The relationship between mobile dunes bordering the mouths is an aspect that is little discussed in the literature and that, nevertheless, could have particular relevance in places where this connection is or has been active, as suggested by MTOP/PNUD/UNESCO (1979) for Uruguay. In this regard, in Uruguay, the adjacent beaches of small rivers are frequently characterised by extensive dynamic dune fields.

1.1 Study area and characterisation

The Rio de la Plata (35°00'S, 55°00'W) has a long (38 x 10 km^2) and wide (30 to 240 km wide) micro-tidal estuary (tidal amplitude <0.5 m). It displays a semi-enclosed shelf marine area at its mouth and a river paleovalley called 'Canal Oriental' on the north coast, which favours the river discharge and transport of sediments to the adjacent continental shelf (López Laborde and Nagy, 1999; Nagy et al., 2002). Total yearly river outflow varies between <20,000 m^3/s and >30,000 m^3/s during dry and wet years, often associated with La Niña and El Niño events, respectively (Nagy et al., 2008b). As a consequence of this extreme variability, clear marine water or turbid freshwater can be found respectively in the surveyed outlets located in the outer (marine) region of the Río de la Plata estuary (RdlP) (Fig. 1).

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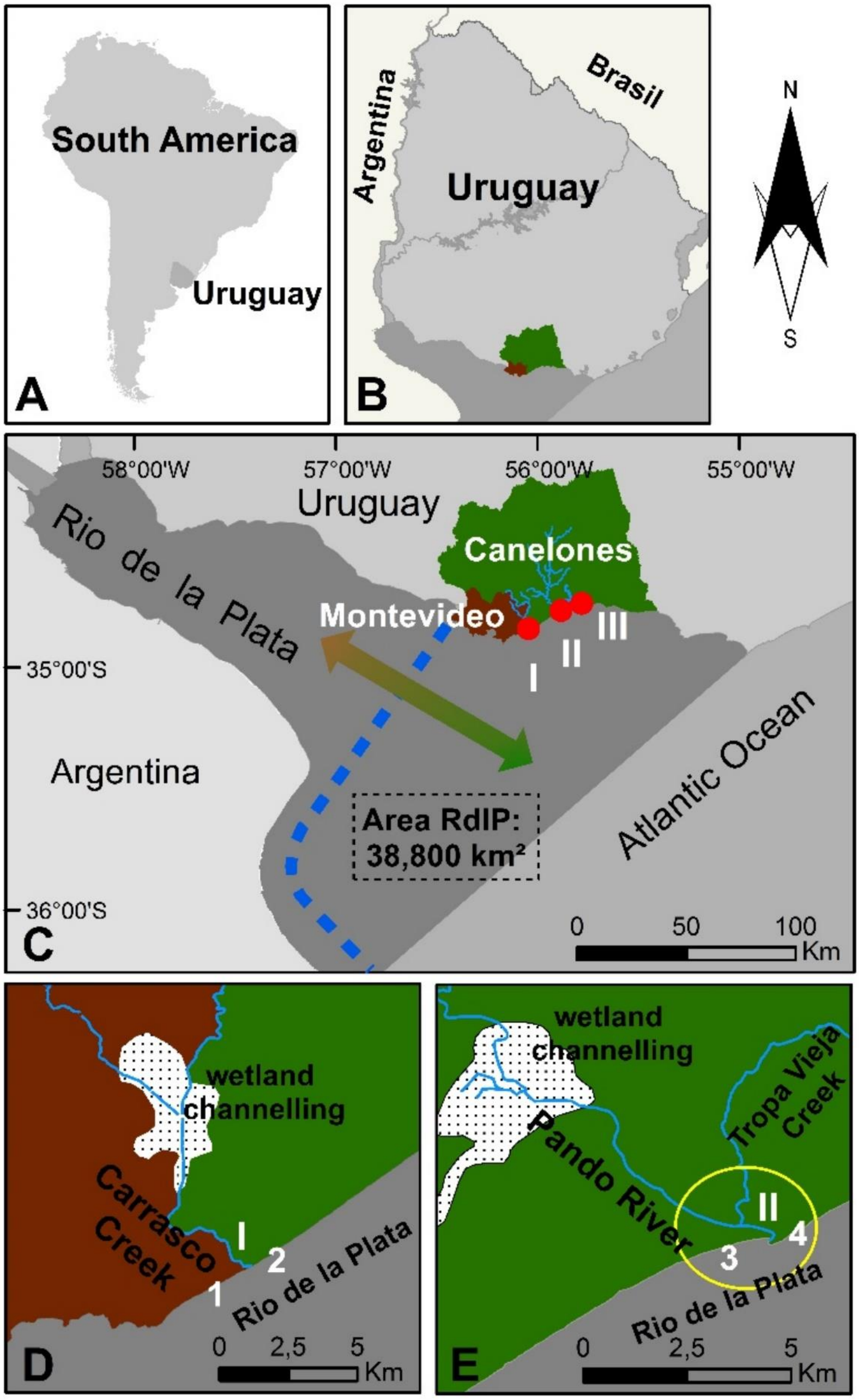

Fig. 1. Location of the study area. A) Top left: South America. B) Top right: Uruguay. The local sub-national government of Montevideo (brown). The local sub-national government of Canelones (green). C) Centre: Río de la Plata estuary. Typical location of the limit between fresh (tidal river) and marine (outer) waters (dotted blue line); estuarine front (arrow) showing the river- and seaward water displacement under severe river outflow and wind forcing; location of the Carrasco Creek (I) and Pando River outlets (II), Atlántida (III). D) Bottom left: Mouth of Carrasco Creek and adjacent beaches 1) Carrasco, 2) San José de Carrasco. E) Bottom right: Mouth of Pando River and beaches, 3) El Pinar, 4) Neptunia. Yellow circle allows correlating the position of the lagoon in Figure 4.

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The mouths of the Pando River and Carrasco Creek, are estuarine sub-systems of the RdlP since the slope in their outer sections is almost nil. For this reason, they are subjected to the entry of brackish water by the effects of tides and winds (Nagy et al., 2008b). These outlets and their adjacent beaches were analysed to study the interrelations between the dune systems and the lower course of the drainage pathways in the coastal sedimentary balance.

The mouth of the Pando River has received several impacts, and as a result of them has undergone modifications, not only in the flow of sediments but also on its hydrological regime (Gutiérrez and Panario, 2005; 2006; Gutiérrez, 2010). The mouth of Carrasco Creek has not suffered significant adverse impacts on the sand cycle, and in turn, due to works carried out in its basin, it has received new inputs of sandy sediments (Gutiérrez, 2010). These works consisted in the construction of drainage channels in a wetland upstream, located on Holocene sandy marine sediments.

The beaches, in which these small rivers outflow, are in "dynamic equilibrium" (*sensu* Short, 1999), because the entrance of sand by different routes is equivalent to its discharge, mainly by littoral drift (Panario and Gutiérrez, 2005; 2006; Gutiérrez and Panario, 2006). Thus, a fundamental component of the coastal sedimentary dynamics (Fig. 2) is the existence of dune fields that, moved by the wind, dump significant volumes of sand into the drainage channels. When the transport capacity of these channels increases, during heavy rains, they provide sediments to the sea that are then transported by coastal drift, feeding the beaches in the direction of the dominant littoral drift (Panario, 1999; 2000; Gutiérrez and Panario, 2005).

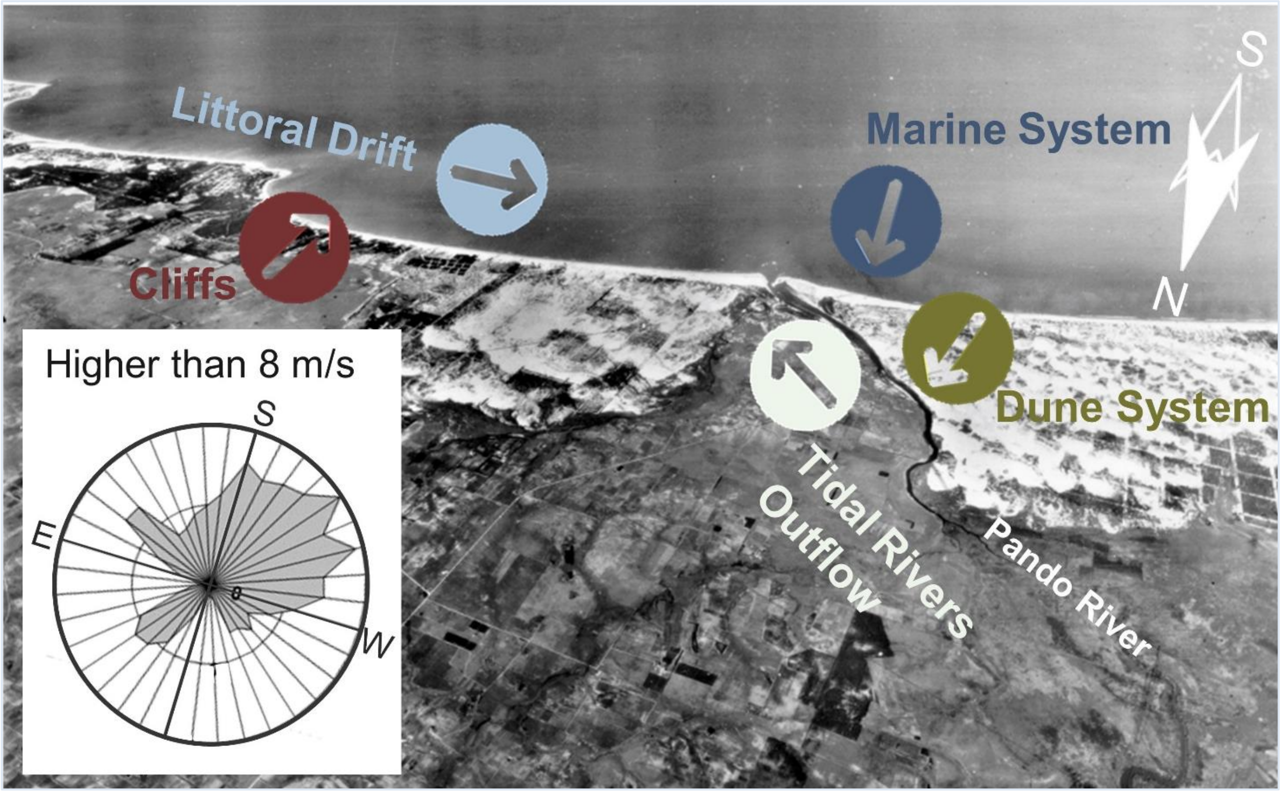

Fig. 2. The cycle of the sand and sources of sediment contributions plotted on the aerial photo of the year 1945 (flight of the Trimetrogon). Strong winds (over 8 m/s) able to move significant amounts of sand are plotted inverted to facilitate the understanding of the dune dynamics at the mouth of the Pando River. The oblique aerial photo was taken from the continent (towards the S). Photo: Military Geographical Service (SGM).

A coast with a sedimentary balance close to zero indicates that the processes of erosion and sedimentation are compensated, oscillating dynamically around an equilibrium situation. On the contrary, if the sedimentary balance is negative, it indicates that erosion predominates and if it is positive, it suggests that sedimentation prevails (Correa et al., 2009). The coast naturally erodes every year, mainly due to storm surges, and it is usually compensated with periods of sedimentation throughout the same year (Wright and Short, 1984). Only when the sedimentary balance shows a long-term erosion trend, due to for example SLR or the increase of the energy of the storms (Correa et al., 2009), or when the sediment inputs have been interrupted due to human action or depletion of the stock, coastal erosion can generate severe environmental, social and economic impacts (Muñoz-Vallés and Cambrollé, 2014).

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1.2 Background

The separation of natural and anthropogenic factors in coastal dynamics is a difficult task, because it is subject to periodic fluctuations that go from diurnal or seasonal cycles, to interannual variability like "El Niño" Southern Oscillation (ENSO), decadal ones like the Pacific Decadal Oscillation (PDO), or multidecadal as the Atlantic Multidecadal Oscillation (AMO). Besides, periodic movements must be added as a result of climatic variations, of marine currents, of subaquatic sediment reserves, etc., whose origins may be preterit and triggered at a particular moment by inertial effects (Gutiérrez and Panario, 2005). In fact, the sedimentary balance in the coastal areas of the outer region of the RdlP depends to a great extent on the littoral drift (Gutiérrez and Panario, 2019) that in turn depends on the balance of winds whose prevalence changes with time (Gutiérrez et al., 2015), plus the action of the relatively constant swell.

In recent years, the component of strong winds from the S and SW sectors has decreased (Bidegain et al., 2005) making possible to argue, also supported by historical and paleoclimatic documentation (Politis, 1984; Iriondo and Kröhling, 2008), that prior to the nineteenth century, their frequency would have been higher. Several authors argue that during the eighteenth century, the influence of a climatic oscillation called "Little Ice Age" in the Pampean region caused an increase in aridisation (Bracco et al., 2011; 2014; Iriondo et al., 2011; del Puerto et al., 2013), while from the mid-twentieth century and to present there is an increase in average annual rainfall (Nagy et al., 2015). Consistently with the above and according to Iriondo and Kröhling (2008), in that colder and drier period than the current one, there was a higher frequency of dry SW winds in large part of the coast, being the W to E component of the littoral drift more significant than currently.

Among the drivers of change, the introduction of exotic species stands out. The vegetation on the coast plays a fundamental role in the dynamics of sandy beaches because native plant favours the construction of the primary dune. However, it is harmful when afforestation or invasion of exotic species (e.g. *Carpobrotus edulis*, *Acacia longifolia*, among others) interrupt the normal flow of sediments between the dunes and the beaches or between the dunes and the creeks or rivers flowing to the RdlP (Panario and Gutiérrez, 2005; 2006).

The dunes located in areas close to the outlets of the coastal watercourses and the dune fields that passed behind the capes were forested as of the 1940s (Panario and Gutiérrez, 2005; Gutiérrez and Panario, 2019). This afforestation which interrupts the recirculation of the sand could be considered as one of the most substantial impacts that contributed to the widespread erosion of the beaches of the outer region of the RdlP. Due to this erosion, numerous civil works were carried out from the 1970s, such as the construction of groins, which were not adequate for local environmental conditions (Gutiérrez and Panario, 2005; 2019; Panario and Gutiérrez, 2005), as shown in other similar situations (Marshall and Banks, 2013). Afforestation, in general, has been the starting point of extended urbanisation and of the following construction of infrastructures (houses, boardwalks, streets, retaining walls), which fixed the area of dunes located behind the foredune, definitively interrupting the sediment contributions from this component of the sand cycle.

2. Materials and methods

Two study sites were selected: 1) The mouth of the Pando River (El Pinar and Neptunia beaches, located respectively to the W and E), with evidence of interactions between the dune system and the coast. 2) The mouth of the Carrasco Creek (beaches of Carrasco and San José de Carrasco located respectively to W and E), without significant contributions of wind-sand (where there is no presence of active dunes since the first record obtained in 1939).

A multi-temporal analysis was undertaken, using remote sensing, GIS techniques, and historical information. ArcGIS 10 was used for georeferencing and analysing the data. The study consisted of 27 remote sensing surveys (1928-2002) of Pando River mouth, and 19 (1939-2008) of Carrasco Creek mouth respectively (Tab. 1), obtained from the archives of the Local sub-national governments of Montevideo (IdeM) and Canelones (IMC), the National Directorate of the Environment (DINAMA) and Hydrography (DNH), the Air Force Aerospace Remote Sensing Service (SSRFAU), the Military Geographic Service (SGM), Google Earth satellite images, an aero photogrammetric survey of the mouth of the Pando River, and military cartography from the SGM. These extensive series are infrequent in this type of analysis, and allow diminishing the error range of the analysed trend.

According to Gutiérrez et al. (2015), since the discontinuous time-series of records cannot match ideally with the occurrence of human interference and climate events, it is essential to obtain as many documents as possible. The images captured have different original scale, most are black and white and the most recent in colour. Some oblique images were also obtained that were used as a reference for the evolution of the system. The series of aerial photographs were scanned at 1200 dpi, and the Google Earth images were downloaded in the best possible resolution. The UTM (Universal Transverse Mercator) Zone 21S projection and WGS84 datum were used.

The georeferentiation of the images of the Carrasco Creek was carried out using a detailed mapping of the wall of the waterfront surrounding the adjacent beaches of Montevideo made by the Department of Geomatics of the IdeM. This map was created by orthorectification and checkpoints from differential GPS with sub-meter relative accuracy, allowing minimising errors between images. Therefore, it was assumed a margin of error of ± 0.50 m in the relative georeference between images.

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Tab. 1. Remote sensor metadata obtained for the mouths of the Pando River and Carrasco Creek. Legend: CCG: Global Change Commission, DINAMA: National Directorate of the Environment, IdeM: Local sub-national government of Montevideo, IMC: Local sub-national government of Canelones, SSRFAU: Air Force Aerospace Remote Sensing Service, SGM: Military Geographic Service.

Date	Pando	Carrasco	Scale	Source
1937, May 19		■	--	SSRFAU
1939		■	1/5,000	IdeM
1943, March 14	■		1/40,000	SGM
1945, January		■	1/10,000	IdeM
1951, October 22	■		1/20,000	SSRFAU
1954, May 14		■	1/15,000	IdeM
1954, May 17		■	1/30,000	IdeM
1960, October 25	■		1/20,000	SSRFAU
1961, April 10		■	1/15,000	IdeM
1961, December 21		■	1/15,000	IdeM
1964, September 14	■		1/20,000	SSRFAU
1966, January 27	■		1/20,000	SGM
1966, December 26	■		1/20,000	SGM
1967, June 13	■		1/40,000	SGM
1970, December 07		■	1/10,000	IdeM
1971, January 26	■		1/10,000	SSRFAU
1971, August 26	■		1/10,000	SSRFAU
1973, October 27	■		1/10,000	IdeM
1975, January 21	■		1/20,000	SSRFAU
1976, February 06	■		1/10,000	SSRFAU
1976, June 17	■		1/20,000	SSRFAU
1977, May 13	■		1/20,000	SSRFAU
1978, April 26	■		1/20,000	SSRFAU
1979, March 29		■	1/10,000	IdeM
1980, January 12	■		1/50,000	SSRFAU
1980, May 25	■		1/20,000	SSRFAU
1982, February 13	■		1/20,000	SSRFAU
1984, December 4	■		1/10,000	SSRFAU
1985, December		■	1/10,000	IdeM
1987, March	■		1/40,000	SGM
1990, June 2	■		pixel 25 m	SPOT XS
1991, May	■		1/5,000	IdeM
1994, May -June	■		1/5,000	DINAMA
1995, October 23	■		1/10,000	SSRFAU
1996, January 22	■		1/5,000	SSRFAU
1996, June	■		1/40,000	IdeM
1997, April	■		1/5,000	DINAMA
1998, December 1	■		pixel 0.75 m	CCG
1999, November 16	■		1/20,000	SSRFAU
2000, April 25	■		1/10,000	SSRFAU
2003, October 23	■		1/10,000	IdeM
2000, November 24	■		1/20,000	SSRFAU
2001, January 21	■		s/d	SSRFAU
2001, November 21	■		1/25,000	SSRFAU
2002, March	■		s/d	DINAMA
2002, May	■		pixel 0.20 m	Pyke y Cia
2004, May		■	s/d	IdeM
2006, September 6		■		Google Earth
2006, November 12		■	s/d	IMC
2007, September29		■	s/d	IdeM
2008, April 30		■	1/10,000	Google Earth

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In the Pando River, the SGM cartography was used as a base to georeference the images and to minimise errors between images as suggested by Gutiérrez and Panario (2005). The first image used was from 1987, and reference points were searched with the previous immediate photo. The reference sequence was made always taking the closest image in time which is repeated until the present.

This methodology allowed referencing the entire series of pictures on the same cartographic basis, thus minimising the deformations and errors in similar terms between them. In all cases, an average relative error of ± 3 m is assumed for the georeferencing process of images. To better understand the long-term morphological changes, maps of the eighteenth century and early twentieth centuries were also included (Tab. 2). The history of the significant anthropic interventions in both basins was compiled from the studied period through unpublished data, cartography, toponymy and grey literature searched through personal communications with researchers. For the Pando, the oral transmission of families settled in the area that goes back to the 19th century was also used.

The digitalisation of shorelines was conducted at a scale of 1:3,000, as proposed by Ciavola et al. (2003), Gutiérrez and Panario (2005), and Armaroli et al. (2006). To select indicators of the shoreline, only those identified in the entire time-series of records were used. These were:

- Pando River mouth: The *previous high tide high - water level* (PHTH-WL; Boak and Turner, 2005) is employed because relatively large differences between tides produce a minimal error in the horizontal cartographic translation of the coastline because the segment of the beach above the high tide level is the one with the greater slope in the cross-section thereof (Gutiérrez et al., 2015).
- Carrasco Creek mouth: The *wet/dry line or runup maxima* (WDL-RM; Boak and Turner, 2005) was used. This line indicates the erosive - constructive limit set in the maximum range of the wave, which is neatly identifiable by the difference in tone on aerial photographs and is perceived on the beach by a change in shape, from a concave profile to a convex one, with a clear break in slope angle.

Polygons were plotted on all surfaces where beach surfaces were found as proposed by Gutiérrez and Panario (2005) and Gutiérrez et al. (2015) to overcome the uncertainty associated with estimating changes by random transect method.

A methodological artefact was used to determine the losses and gains (areas) of both outlets between a position of the coastline considered as the base year and the polygons that exceeded or detracted from the zone concerning the said year. For this purpose, two perpendicular transects were drawn on the most recent coastlines, one on each beach that served as an external boundary to measure their historical evolution (Fig. 3). The location of these transects delimits the area with indications of substantive changes during the analysed period. The results were plotted as a cumulative gain-loss function during the investigated period.

To estimate the volumes contributed from the dunes on the contact front with the channel, calculations were made with the Fryberger equation (Fryberger, 1979) adjusted by Panario and Piñeiro (1997) to local conditions from wind data (see Fig. 2) of the weather stations Carrasco (National Institute of Meteorology-INuMet), and Punta Brava (Oceanography, Hydrography and Meteorology Service of the Navy-SOHMA).

$$UV = [V2(V-Vt)]/100 \times t$$

Where,
UV = vector units,
V = wind speed,
Vt = speed threshold required to start moving sand
t = number of measurements in a given time.

The vector units are converted to $m^3\ m^{-1}\ year^{-1}$ using the relationship proposed by Fryberger et al. (1984) where 14 UV is equivalent to 1 $m^3\ m^{-1}\ year^{-1}$.

Tab. 2. Cartography metadata obtained for the mouths of the Pando River and the Carrasco Creek. Legend: NMM, National Maritime Museum, SGM: Military Geographic Service.

Chart	Publication year	Additional information	Source	Scale
"Carta esférica del Río de la Plata desde su desembocadura hafta Buenos-Ayres"	1798	surveyed in 1789 and rectified in 1794	NMM	ca. 1:550,000
Sheet E - Carrasco	1920	surveyed in 1917	SGM	1:20.000
Sheet IX-29 - La Unión	1930	field support 1928	SGM	1:50.000
Sheet 24 - Montevideo	1933	---	SGM	1:200.000
Sheet J-29 - La Unión	1984	field support 1984	SGM	1:50.000
Sheet J-29-a - El Pinar	1988	field support 1987	SGM	1:25.000

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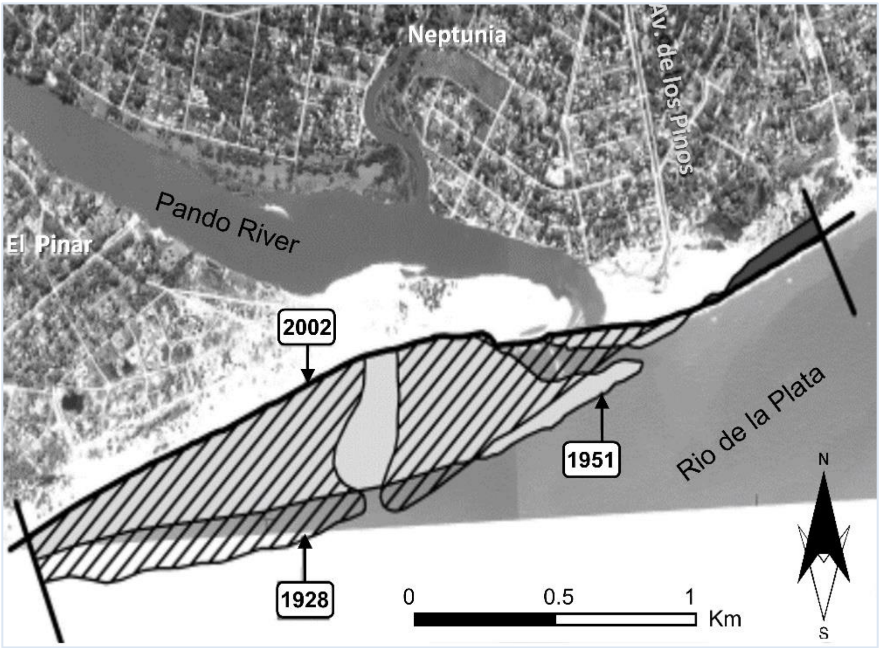

Fig. 3. The thick black line indicates the baseline of May 2002 (base year) with the two perpendicular transects. The striped area shows the mouth of the Pando River for the year 1928 (first available chart). Below, in a light grey solid colour, the mouth in 1951 is shown. Aerial photography: May 2002, Pyke & Cia. S.A.

In turn, sand contributions from the basin were analysed, estimated from data obtained in reservoirs of basins with similar characteristics in the studied region, such as the Canelón Grande (MTOP/PNUD/UNESCO, 1979), and adjusted by the size of the basin, the flow in m^3/s, and the percentage of bottom load of the total produced sediments.

A sampling of the bottom sediments of the lower section of the Pando River was carried out. Sediment samples were analysed by sieving and the International Method of the Pipette (Soil Management Laboratory of the MGAP, Day, 1965). The flow of circulating sand by littoral drift was estimated from information of the MTOP/UNDP/UNESCO (1979) report on the volume of sand captured by the groins upstream of the drift, immediately after its construction.

Topographic transects were carried out to determine the sedimentary volume of the beach to quantify the loss of sand over the analysed period and the relationship of these losses with the fixation of the dune field by afforestation and urbanisation.

The univariate statistical analysis was carried out for the data sets obtained for each study site. The selected statistical indicators were: central tendency and data dispersion: mean, median, mode, standard deviation, variance, the coefficient of variation and R^2.

3. Results and Discussion

3.1 The mouth of the Pando River

The El Pinar and Neptunia beaches (located at the W and E of the mouth of the Pando Stream, respectively), are micro-tidal dissipative beaches, evolving from dissipative to intermediate in El Pinar, as it distances from the mouth. In its original condition, this coastal area was mostly associated with active dune environments or with sparse vegetation cover. In the cartography of 1789 (Fig. 4), there is a lagoon located at the mouth of the Pando River, showing a closed bar (National Maritime Museum, 1789), typical of the climatic conditions of that time ('Little Ice Age' 1550-1850; Politis, 1984).

Little Ice Age, was a colder/dry period which triggered the transport of inland wind sand throughout the world (Wilson et al., 2001), which promoted the closure of Pando River mouth. A similar process has been described in other coastal regions of Uruguay (e.g. Valizas River mouth, del Puerto et al., 2013; Inda et al., 2017). The thin layer of clay-silty sediments of this lagoon is observable nowadays below coverage of variable thickness of wind-sands, indicating its brief permanence. This map was the first reference on this fact, although oral tradition has kept the memory of the event.

The Pando River, until the beginning of the 1920s, flowed into a wetland formed by the colmatation of another bigger lagoon (presumably of Holocene age), located upstream, which at that time drained into the RdlP through a channel. Between 1912 and 1920, the wetland was channelled and the river dammed behind it, to maintain the water height. Such a human intervention changed the channel hydrology determining the loss of its regulatory power of the 900-hectare wetland. Between pulsations of floods produced by torrential precipitations, the outlet has been dominated by the littoral drift. The map of the SGM (1923) shows the wetlands and the canalisation works carried-out.

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Fig. 4. Map of the year 1789. The yellow circle indicates the location of a lagoon at the mouth of the Pando River (*Arroyo de Pando*) and the closed bar. Source: National Maritime Museum (1789).

3.1.1 Physical characterisation

The granulometry of the El Pinar and Neptunia beaches is similar, fine to medium sand, provided by the east drift. This sand was partially recirculated at the Pando River outlet between the dunes of the river and the beach, as will be discussed later.

In the beach area of El Pinar, the sand is slightly thicker towards the berm than on the low beach, while in Neptunia the granulometry does not vary substantially due to its position. The orientation of the Neptunia beach has changed over time as the section of the outlet receded. Whereas for the year 1928 the normal directions to the tangents of the beach areas located adjacent to the W and E of the mouth were N9.2ºW and N27.3ºW respectively, for the year 1960 they were N14.5ºW and N31.2ºW, respectively. Currently, the location is N17.3ºW, which means that the swell reaches this part of the beach almost parallel to the coast. On the shore of El Pinar, the orientation varies to N24ºW generating a higher angle of incidence of the swell, which implies an acceleration of sediment transport in the W direction; notwithstanding this, the bar at the mouth of the Pando River and other drainage channels present in the same beach arch, such as Carrasco Creek, have an easterly direction.

3.1.2 The recent evolution of the mouth of the Pando River and its dynamics

By the year 1930, Legrand (1959) described two dune systems on the left bank of the Pando River. At El Pinar beach, this dune field had a transgressive front with several kilometres in length, directed inland and parallel to the river (Fig. 5). The afforestation of El Pinar interrupted the flow of sand from this transgressive front, limiting the contribution of wind-sand to the dune ridges, except for a few lobes (blowout). In the aerial photos of 1943, the beginning of afforestation was observed with the implantation of *Acacia* fences (invasive alien species-IAS) to subsequently implant trees of the *Pinus* genus in the dune systems of El Pinar. Such afforestation became notorious in the study area from the 1950s, and it was observed massively implanted in the images in the 1960s, in which urbanisation was also consolidated.

In the 1940s, afforestation with eucalyptus and pine trees began in Neptunia, which was carried out even on the dune system itself. The trees of high bearing, once they produced a repair to windward, favoured the formation of new dunes in their front, generating so a new space, which also was afforested. This process resulted in the planning to urbanise in what was previously a beach (Fig. 6).

During stormy weather the waves reach the forested dunes where the roots of the trees maintain the verticality of the cut produced in the dune, causing a change in its dynamics, which is manifested by an accelerated retreat of the dune, linked to the friability of the sands of the substrate (the dune). This process facilitates the displacement of the bar inland, quickly affecting the area with projected urbanisation (see Fig. 6). When severe beach erosion occurred in consolidated urbanisation located in the direction of the drift to the East (Atlántida), the Ministry of Transport and Public Works (MTOP) began the construction of groins, in the year 1970, which continued

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until the beginning of the 1980s. However, these hard structures contributed to accelerating the erosion process. From the penultimate pier built and due to the loss of sand generated by the rip currents, the erosion provoked a setback, of more than 11 meters, of a sedimentary cliff 7 meters high (of quaternary origin, located after the penultimate jetty) between 1985 and 2003 (Gutiérrez and Panario, 2005; 2006). The groins were built due to the strong coastal erosion observed in Atlántida which is located on a cape that was permeable to the transit of sand between its two beach arches. Sand was transported by land towards the E from a field of mobile dunes, and by the RdlP towards the W. The afforestation of these dunes, consolidated in the 1940s, interrupted the feeding of the beach located in the direction of the drift, generating a deficit of sand that started from the W of the cape.

Fig. 5. Panoramic view of the mouth of the Pando River dated May 19, 1937. Source: Uruguayan Air Force Remote Sensing Service (SSRFAU).

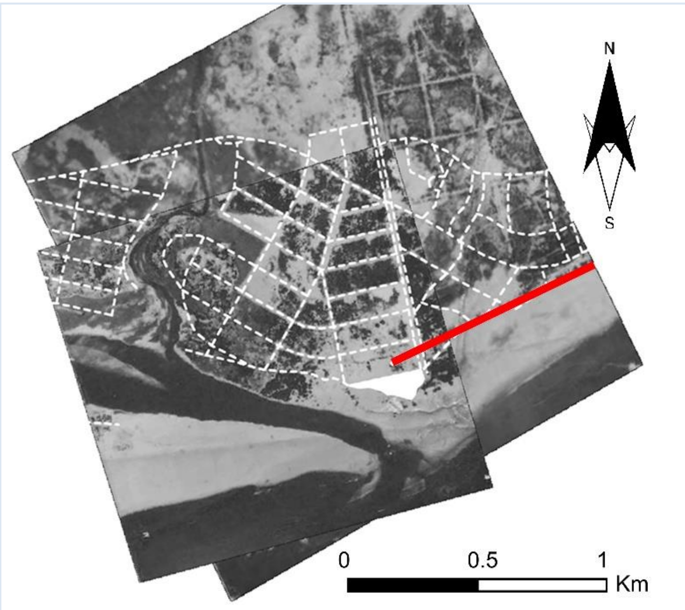

Fig. 6. Photo of October 25, 1960, of the forested Neptunia beach, displayed above the picture of October 22, 1951 (both in scale 1: 20,000) showing the original location of the dune system (indicated in thick red stroke). The urbanisation is shown in white dotted line; the square closest to the RdlP (blank) had already disappeared, as well as part of the street in the next square and the waterfront of the stream. Source: aerial photographs, SSRFAU.

At the beginning of the 1990s, sand extraction was authorised from the dunes of the bar located to the west of the outlet, which was made in some sites to such depth that the water table flowed to the surface. Since 1995, the beach has suffered a sharp retreat.

Over the period 1928-2002, the beach area adjacent to the outlet decreased 683,357 m^2 along a coastline of 3,220 linear m, representing 9,234 m^2/year, which is close to the theoretical value of the annual lost area of 8,069 m^2/year calculated by regression with a highly significant trend

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(p <0.0001) (Fig. 7). This loss of coastline is a considerable impact, especially in the beach of Neptunia (located towards the East). The comparison of the images and cartography existing from 1928 to the present shows a 480 m retreat of the coastline of El Pinar beach, as pointed out by Gutiérrez and Panario (2005), although this retreat only became noticeable and persistent from 1950 onward. However, the orientation of the lower section of the Pando River, which between 1928 and 1936 was N-S, as early as 1943 began to move eastward, producing a turn of almost 80 degrees.

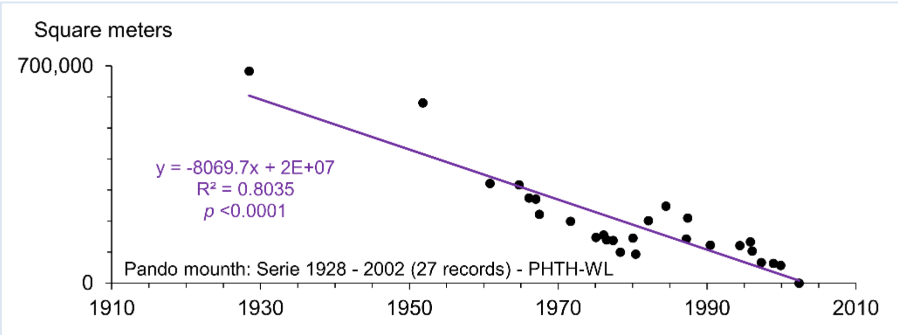

Fig. 7. Pando River mouth. Historical evolution of the retreat of the coastline between 1928 and May 2002, made up of all the records obtained for this outlet (27 records), using the *previous high tide high - water level* (PHTH-WL) as a proxy. The loss of coast was highly significant (p <0.0001).

3.1.3 The sedimentary balance of Pando River mouth

The Pando River basin has an area of 973 km², and it is assumed that it contributes 240 tons/km²/year of sediments (MTOP/PNUD/UNESCO, 1979). Syvitski et al. (2005) reported that the global average of sandy sediments contributed from river basins can be estimated in 1.1% of the total sediments that reach them. However, for the large Uruguayan rivers this volume has been evaluated in the order of 2% (Urien, 1967), and for the smaller ones, it has been determined to be of ≈2.5 to ≈10% (MTOP/PNUD/UNESCO, 1979). Therefore, of that total volume of sand-sized sediments contributed from the basin, considering that there is a small dam located at the beginning of the wetland, it was deemed to be greedy to use the lower value. The average size of the basin and its characteristics (undulating relief, deep soils, agricultural livestock use) reinforce the assumption of an amount of ≈3%, a value slightly higher than that measured in the Canelón Grande Basin, which is more substantial.

Of the total sand contributed by this basin (3%), it was determined from the analysis of the bottom sediments that 5.6% was coarse to very fine sand, and its apparent density was 1.6, from which it is deduced that the contribution by this source would have a value of ≈245 m³/year.

To determine the importance of the contribution of the dune system in direct contact with the river bed, first, the length of this contact was determined through photointerpretation, giving a result of 3,100 linear meters of touch with the dune field.

The potential transport is caused by strong winds (10 to 12 m/s) and very strong winds (15 to 20 m/s) in a bimodal form, resulting from combining the exponential decay of the frequencies with the cubic potential increase of the weight, in which the adjusted for local conditions model of Fryberger (1979) attributes to rare but intense winds. Similar bimodality has been observed in other areas of the Atlantic Uruguayan coast such as Cabo Polonio, La Paloma and Punta del Este, from which it can be deduced that a good part of the transport can be generated during only 6 or 7 days a year (Panario et al., 2008), which is sensitive to the wind patterns change (see Box 1).

Based on the profile of winds from the meteorological stations of Carrasco and Punta Brava (Piñeiro, 2010) located less than 30 km away from the studied area, the directions capable of supplying sand to the rivers were selected, namely, S, SW, W and NW, resulting in a transport of sand per linear meter of contact of 22 m³/year.

Multiplying the volume transported by the 3,100 m of contact, a net annual contribution from the dune system of 68,200 m³ is obtained. To estimate since when this contribution was negligible, the afforestation process of the area was analysed. The fixation of the dunes by afforestation started in the 1940s and, for El Pinar, dunes were fixed in 1960, when urbanisation increased significantly reaching the river margin. Therefore, it was estimated that from 1960, the wind contributions became negligible at El Pinar. For the period between 1960 and 2002 (year zero for the count), a volume of 2,864,400 m³ was calculated, as the total contribution lost by this component of the coastal sedimentary cycle at the mouth of the Pando River.

Given that, for the period 1960-2002, the measured beach retreat involved a loss of 312,524 m² and considering an average beach prism height of 3 meters (including berm and protodune), it can be estimated that the direct response of the system through the retreat of the coastline was about

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964,574 m³ (Fig. 8). Therefore, if 964,574 m³ are subtracted from the direct contributions not made by the dune system, a contribution gap of 1,899,826 m³ would still have to be explained, for the studied 42 years, which the system must replace from other sources, or the retreat of the coastline should have been higher, if it had not had an additional contribution of 45,234 m³/year. To understand why there was no significant retreat of the shoreline, given the estimated annual shortfall of 45,234 m³/year and to understand the possible sources of compensatory contributions of sand to the system, the other components of the sand cycle are analysed:

1) The inputs from the cliffs. The possibility of an increase of the transport by the littoral drift in this zone, due to the contributions of the retreat of the cliff of more than 11 meters by 7 meters of height located in the direction of the drift is not to reject.
2) The intense erosion of the eastern margin (Neptunia) due to the migration of the external section of the Pando River.
3) The entry of the sand stock that according to Gutiérrez and Panario (2005) was accumulated in the form of an underwater fan in front of the mouth, while the contributions of the dune system were active.
4) The inputs from subaquatic transport (resulting from littoral drift) were 70,000 m³/year (MTOP/PNUD/ UNESCO, 1979) which explains the existence of dune systems on the east coast of the mouth. Of these sediments in transit, it is estimated that approximately 48,860 m³/year are removed from the beach by the waves and then re-transported by the E, SE and W winds, which are the directions from which sand is transported to the fenced dune system. For the conditions of the RldP, the transport of winds from the S and SW was not considered, because the elevation of the water level they produce prevents the transport of sand by wind on the beach. This value (48,860 m³) was verified empirically, based on the sand retained by a fence on the shore of Neptunia (September 1, 2005, and January 21, 2006).

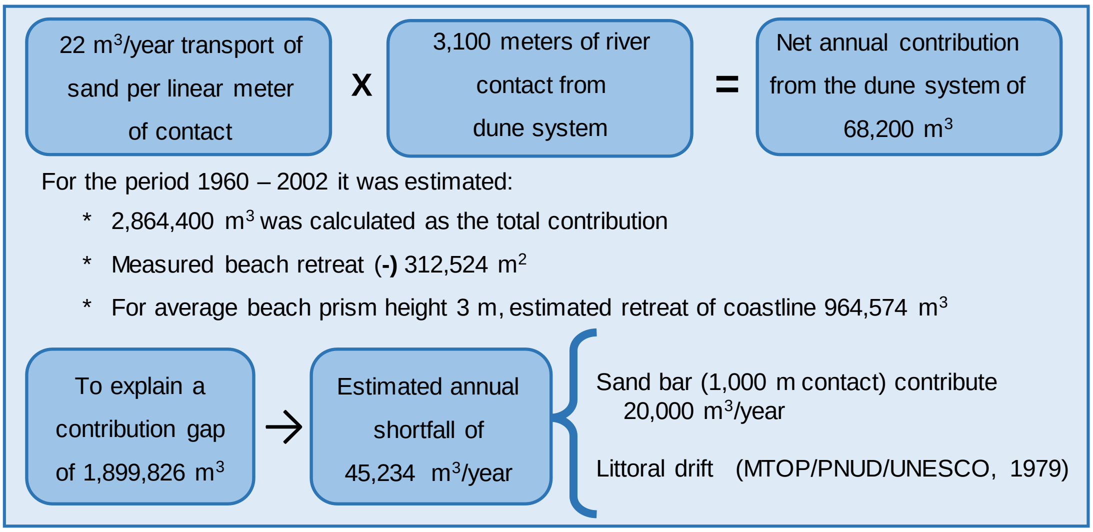

Fig. 8. Summary of of Pando River outlet sedimentary balance.

Therefore, by multiplying the potential contribution transported by the drift and retaken by the wind, estimated as being 48,860 m³/year for the 42 years of the period under analysis, a value of 2,052,120 m³ is obtained, resulting in a surplus of 152,294.00 m³ for the period, which means 3,626 m³/year, which is a proper adjustment.

3.2 Carrasco Creek mouth

The lands surrounding both banks of the Carrasco Creek were described in the GMS cartography of the year 1920 as "sandy terrains" (Fig. 9) and not as sandbanks or dunes, as mobile dunes are usually called in this type of chart. In the aerial photos before the time of the marsh desiccation, there was no dune structure, which allows assuming that it did not receive sand transported by the wind in its lower channel. The Carrasco Creek can be characterised geomorphologically as a natural channel that drains the adjacent marshes, formed by the colmatation of a presumably Holocene lagoon that received the waters of the Toledo and Manga Creeks.

3.2.1 Physical characterisation

The beaches of Carrasco and San José de Carrasco are located west and east of the mouth of Carrasco Creek, respectively. These beaches are classified as dissipative to intermediate and are part of the same arc as El Pinar and Neptunia beaches (being located upstream in the direction of the drift and separated by less than 15 km each other), and sharing the same physical characterisation. The normal directions to the tangents of the beach areas located adjacent to the mouth of the creek are N26.3ºW and N36ºW, respectively.

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As in the case of the Pando River, the strong SE winds move the bar towards the East, in the opposite direction of the dominant drift, since they build a higher berm, in a direction opposite to the swell. In the area of the outlet, the beach is oriented to SE, which is why the most persistent swell wave impacts (like in the Pando River) almost normal to the coast producing a littoral transport of E-W direction.

3.2.2 The recent evolution of the mouth of Carrasco Creek and its dynamic

The year 1939 is taken as the initial date (year zero) of the historical development, corresponding to the first photographic record. The trend analysis of the mouth of the Carrasco Creek was made with a series of 19 images (period 1939-2008) showing a growth of the beach area of 202 m^2 /year (significant at 85%) (Fig. 10), which was obtained by using the proxy *wet/dry line or runup maxim*a (WDL-RM; Gutiérrez et al., 2015). The analysis of the multitemporal series of the outlet showed that, although there was a trend towards the growth of the beach area, fluctuations of the location of the coastline concerning year zero prevailed.

The evolution of the beach sector adjacent to the outlet fluctuated following a similar pattern like the one shown for Montevideo beaches (Box 2) located a short distance to the W (Gutiérrez et al., 2015). However, a difference was that the fluctuations observed at Carrasco beach showed until 1970 a certain pre-eminence towards beach loss, which is then reversed, presumably according to the report of the MTOP/PNUD/UNESCO (1979), when they began to receive significant volumes of sediments as a consequence of the canalization works of the marshes.

3.2.3 The sedimentary balance of Carrasco Creek mouth

The Carrasco Creek basin has an area of 205 km^2, and just as for the Pando River, a contribution of 240 tons/km^2/year of sediments can be assumed (MTOP/PNUD/UNESCO, 1979), and also a 3% of sandy sediments contributed from the basin are assumed. Of the total sand added by this basin (3 %), it was estimated that, as for the Pando River Basin, 5.6 % of that value was sand of coarse to very fine diameter, and its apparent density was 1.6, from which it is estimated a contribution from this source of 51 m^3/year. It should be taken into consideration that before the channelling of the marshes the contributions should have been negligible given that the total sandy sediments were deposited in the wetland at the basin entrance.

Since 1973, when the channelling of the creek allowed transporting sediments from the bottom and the margins of the canal, it came to provide an estimated 189 m^3/year from this new source. The wind contributions are recirculated entirely between the bar and the RdlP, and for this portion of the beach arch, the contributions from the RdlP can be considered constant for the studied period since no erosion was found at the drift in the studied area.

3.3 Final remarks

The fixation of dunes through afforestation with exotic species in the Uruguayan coast has been carried out since the 1940s, to be later urbanised. In some cases, this afforestation intended to "transform into a productive zone", some sandy areas, which at that time lacked economic and ecosystemic value.

Thus, the dune systems that recirculated the continental sandy sediments to the coasts from areas near the river mouths were forested, as well as those systems that recirculate the sand transporting it behind the coastal rocky points. This interruption (when fixing the sand with vegetation) of the coastal sediment cycle explains, to a large extent, the coastal erosive process verified in the Uruguayan coast, which began to manifest itself severely in the sixties.

Fig. 9. Chart from 1920, where the wetlands (*Bañado de Carrasco*) of Carrasco Creek (*Arroyo de Carrasco*) and the presence of sandy soils (*Terreno arenoso*) on both banks are observed before the drying works. Source: Map Library, SGM.

This erosive process generated a response from the authorities who implemented hard works according to the state of the art of the time and which were ineffective, and sometimes even increased the erosive processes, or transferred their effects of lack of sedimentary stock to nearby beaches. The models and techniques used were the results of the technology policy transfers, that is, the application of models that proved successful for other conditions of coastal dynamics. The erosion generated

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concern in the coastal communities since part of the coastal infrastructure was lost. The highlight of the problem and its possible solutions was evidenced through scientific studies on the subject and has led to the awareness of the dimension of these coastal processes. Recently, and as a result of this knowledge, even the National Directorate of the Environment (DINAMA) has adopted the policy of preventing the fixation of active dunes, and also tends to reverse this process when it is still possible. The topic of interactions between active dunes and the health of coastal ecosystems should always be taken into account in integrated coastal management and as a measure of adaptation to the SLR and storm surges.

A learned methodological lesson is to make an adequate selection of the coastline proxies (*sensu* Boak and Turner, 2005) for the interpretation of sequences of images to discriminate 1) particular processes of "short-term flooding" (*sensu* Flick et al., 2012) and coastline fluctuations due to episodic storm surges, and 2) coastal erosion with loss of territory or volume of exposed sand (beach prism) due to sea-level rise and/or sediment deficit.

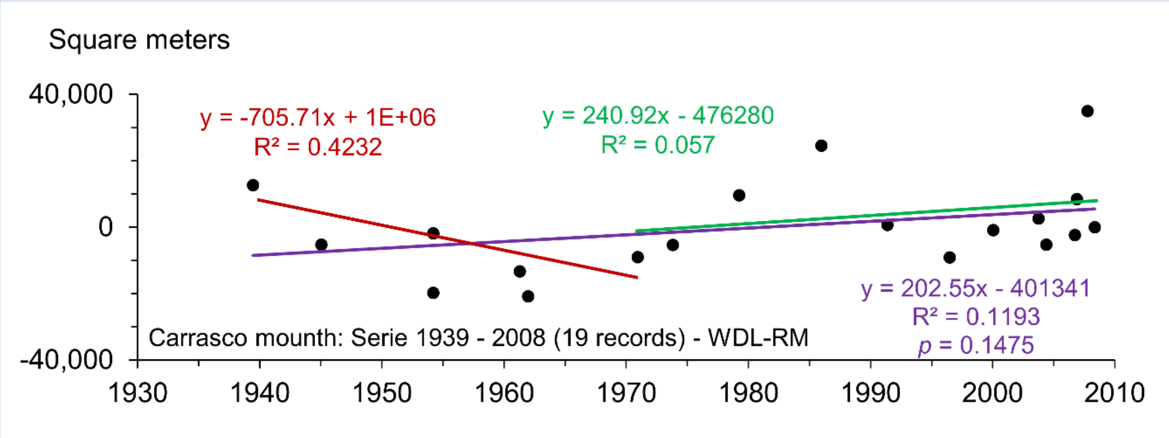

Fig. 10. Carrasco Creek mouth. Historical evolution of the advance-retreat of the coastline (1939-2008: 19 records), using the *wet/dry line or runup maxima* (WDL-RM) as a proxy. The linear regression indicates a slight increase in the beach surface, statistically significant (85 %). The trend of the period 1939-1970 shows a loss (red line), while for the period 1970-2008 it is positive (green line), with a slope slightly more significant than the trend of the whole period, increasing beach surface of 240 m^2/year.

4. Conclusion

The effects of anthropic interventions usually manifest themselves in the coastal system with variable delays, which, in addition to the overlap with the impacts of climatic stressors, makes it difficult to establish clear causal relationships.

This work highlights the importance of the interaction between dune fields and drainage sources in the Uruguayan coast concerning the supply of sandy sediments since they are two orders of magnitude higher than those from the basins. Afforestation of mobile dunes on the Uruguayan coast has been one of the leading causes of decreasing volumes of sand circulating on the shore of the Río de la Plata outer estuary, helping to increase the processes of beach erosion. Other interventions such as the desiccation of wetlands, although it has undesirable environmental effects, in the case studies presented herein, particularly in Carrasco Creek, have helped reduce coastal erosion.

In the case of Pando River (and presumably in other streams of similar characteristics with active dune systems), the high volumes of wind transport allow inferring that by reconstructing the dunes that prevent the escape of sand inland or its return to the Río de la Plata by downwelling, ongoing erosion processes could be reduced.

Beach management policies must often reconcile conflicting interests, which is why they are a tool of particular importance in the land-use planning of coastal zones; therefore, making a precise sedimentary balance in order to foresee the impacts of civil works, as well as eventual climate change impacts, is a crucial factor for the integrated and sustainable management of coastal areas.

Acknowledgment

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Box 1. Climatic and Oceanographic setting.

The Carrasco and Pando tidal rivers outflow to the outer (marine) region of the Río de la Plata micro-tidal river estuary (Fig. 1). This coast is subject to an erosion-accretion cycle related to spring-summer and winter periods, and inter-annual variability due to atmospheric anomalies, e.g., wind direction changes and the consequent swell and littoral drift changes, associated with El Niño and La Niña events. The former is associated with accretion and the latter with erosion (Gutiérrez et al., 2016). The primarily observed wind and sea-level patterns related to this cycle are synthesised as follows:

- There is a relationship between the ENSO-related anomalies of atmospheric circulation and winds. For instance, i) an increase in E-SE-SSE-N winds and a decrease in SW winds (called Pamperos) during El Niño; ii) an increase in SW winds during La Niña (Gutiérrez et al., 2016) associated with the anomalies of sea surface temperature and wind speed; iii) an increase in S, SSE and SE wind directions for the last few decades (Ortega et al., 2013).
- Under both current (1979-2014) and future (centred in 2030) Representative Concentration Pathways climate scenarios (RCPs), there is a slight increase of SE winds along the Uruguayan coast (Nagy et al., 2015).
- The frequency of days with winds higher than 8 m/s increases during spring-summer (Nagy et al., 2008a), whereas the average wind speed and anomaly slightly increase (Nagy et al., 2003; 2008b) during El Niño- La Niña (Gutiérrez et al., 2016).
- Southern winds play a vital role on the Uruguayan coastal dynamics, but with different effects depending on the synoptic conditions and fetch associated with wind speed (Nagy et al., 2008a; Gutiérrez et al., 2015; 2016; Verocai et al., 2015).
- ESE wind direction prevails up to about 7 m/s at the coast, whereas for greater speeds SW and WSW directions prevail (Panario et al., 2008). The former mainly occur during spring-summer and the latter during winter, which is supported by the higher frequency of storm surges able to modify the coastal geomorphology (Gutiérrez et al., 2015) reported by Verocai et al. (2015), and by wave data showing a close match with the prevailing ESE to SE and S wind and swell directions (Panario et al., 2008).
- Sea-level rise (SLR) over the last century reached only 11 cm in Montevideo (Nagy et al., 2007), and, over the previous five decades, above 20 cm in Punta del Este (Nagy et al., 2015) as a result of global climate change and the regional effects of river discharge and winds (Verocai et al., 2015).

Box 2. Trends in Montevideo beaches.

The historical evolution of the beaches located south of the Carrasco Creek has been studied through vertical aerial photographs (since 1927) and old maps of the nineteenth century (Panario et al., 2008; Gutiérrez, 2016). These beaches show a behaviour that responds to interannual ENSO-related variability, in particular, recovery (progradation and increase in sand volume) during El Niño events, and erosion related to the occurrence of strong La Niña events. During La Niña years there is a higher incidence of strong winds from the South and particularly from the SW, while during the El Niño years the winds from N, E to ESE increase (Gutiérrez et al., 2016).

According to Gutiérrez et al. (2016), three storm events coinciding with elevations of 2.11 m Above Mean Sea Level (AMSL) were found corresponding with average daily Southern winds (S) ranging from 24 m/s to 31 m/s. These events can overcome most of the prism beach in most of the study area. Their occurrence from 1921 to 2008 was six times, but only once since 1950. However, Verocai et al. (2015) found a slight increase in the occurrence of events greater than 1.89 m AMSL, capable of modifying the coastal morphology, over the last decade. At the same time, a fluctuating trend in atmospheric energy has been observed, verified by storm surges with maximums at the beginning of the 20th century and minimums between 1960 and 1970, and an increasing trend of the average energy since then, assimilable to the AMO variability (Gutiérrez et al., 2016). Higher intensity and frequency of storm surges and SLR would determine a highly erosive scenario for the coast of Montevideo (Orlando et al., 2019).

The existence of an annual phase detected from yearly images could be indicating a relationship with the Rossby Cycle (biannual fluctuation) because according to Simionato et al. (2005), it modifies the position of the South Atlantic anticyclone (SA High Pressure). However, the general trend for pocket beaches in Montevideo is adjusted to the Bruun Rule (Gutiérrez et al., 2015), standing in the vicinity of 1.7 meters of retreat per cm of MSL ascent (Gutiérrez et al., 2016). These beaches are in the range that complies with the validity premises of Brunn's rule, as proposed by Cooper and Pilkey (2004), as is the case with pocket beaches like Ramírez and Pocitos.

The analysis of the fluctuations of the sedimentary balance in the pocket beaches of Montevideo allowed detecting that, during the periods of increased southern winds, actions were undertaken to reduce their impacts on the urban beaches (Gutiérrez, 2016). The enhanced intensity and frequency of ENSO events, together with SLR and increased storminess, constitute a highly erosive scenario for the Montevideo coast.

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